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# Comparison of Turbine Engine Test Cell Airborne Nanoparticle Count Versus Ambient Background Particle Count

In partial fulfillment of the requirements for the
Degree of Master of Science in Aviation and Aerospace Management

A Directed Project

By

Ryne LaRowe

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Title of Directed Project: Comparison of Turbine Engine Test Cell Airborne Nanoparticle Count Versus Ambient Background Particle Count

For the degree of Aviation and Aerospace Management

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EXECUTIVE SUMMARY

LaRowe, Ryne E. M.S., Purdue University, August 2011. Comparison of Turbine Engine Test Cell Airborne Nanoparticle Count Versus Ambient Background Particle Count. Committee Chair: Dr. Mary E. Johnson.

With the establishment of the National Test Facility for Aerospace Fuels and Propulsion at Purdue University in October of 2009, new equipment has been acquired to measure and classify exhaust emissions. This facility utilizes the Honeywell F109 turbofan and Pratt & Whitney PT-6 turboprop engine test cells to analyze the emissions and engine operation of new alternative aviation fuels. This observational study investigates what, if any difference there is in the amount of ambient residual Particulate Matter (PM) in the turbofan engine test cell when compared to ambient particle count associated with the Purdue University Airport (KLAF) property. The project utilized a Model 3776 Ultrafine Particle Counter from TSI Inc. to measure particle counts in the 2-100 nm range both outside on the airport property and inside the test cell. Random samples were then taken and compared via a 2-sample t- test to see if the test cell has a higher concentration of airborne fine particles than is normally observed at the airport property. The result of this study was an assessment of the environmental impact of the F109 test cell burning Jet-A and recommendations to mitigate or reduce its associated particle count.

# SECTION 1. INTRODUCTION

The aviation community is confronted with the need to evaluate the effect aviation exhaust emissions has on air quality. Particulate matter has become a concern recently due to the lack of information on quantity, and health and environmental impacts. Airports have a large impact on the community and environment wherever they are located. With the increase in air travel, airports worldwide continually expand to accommodate the increased traffic. Residents near airports are potentially exposed to Hazardous Air Pollutants (HAP's) that are gaseous chemicals or extremely small airborne particulate. The goal of this project was to identify if the operation of a gas turbine engine test cell led to an increase in the average fine particle count when compared to the ambient background count of the airport property and if necessary suggest means to mitigate the effects.

## 1.1 Statement of Problem

Is the ambient fine particle count measured in the F109 test cell different from the fine particle count observed on the airport property?

## 1.2. Research Questions

- In what ways did the F109 engine test cell impact local air quality?
- Was the average airborne fine particle count significantly higher in the test cell than what is normally observed at the Purdue University Airport?

- What, if any, measures were taken to reduce or eliminate the effects of an increased particle count?

### 1.3. Scope

The goal of this research was to gather information on the impact of the presence of a turbine engine test cell and determine the average airborne fine particle count in the F109 test cell in the Niswonger Aviation Technology Building and how it compared to the ambient external airport particle count. Information was gathered by direct sampling of the air with a TSI Inc. Model 3776 Ultrafine Condensation Particle Counter.

### 1.4. Significance

The information gathered from this research was used to determine the average amount of fine particles in the air within the F109 test cell. Coarse particulate, or those larger than 2.5 micrometers can be inhaled, however they typically remain in the nasal passage. Fine and ultrafine particles; anything smaller than 2.5 micrometers, are more likely to enter the respiratory system and cause health problems (Miake-Lye, 2008). As a result of determining the air quality impact of operating a test cell, protective measures can be developed to improve conditions within the current test cell or aid in the design of any future test cell additions or expansion projects at the Purdue University Airport.

## 1.5. Definitions

**Aircraft gas turbine engine** - Any gas turbine engine used for aircraft propulsion or for power generation on an aircraft, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines (ARP 1533 Rev. A, 2007).

**Deposition -** An airborne pollutant that reaches the ground by force of gravity, rain, or attaching to other particles (Miake-Lye et al., 2008).

**Emission and Dispersion Modeling System** – EDMS- A complex source microcomputer model designed to assess the air quality impacts of proposed airport development projects (p.1) (Federal Aviation Administration, 2011).

**Elemental carbon** - The refractory carbon found in combustion-generated particulate matter; also known as graphitic carbon (AIR6037, 2010).

**Engine exit plane** - Any point within the area of the engine exhaust nozzle at an axial distance within 0.5 diameters (or equivalent, if not circular) downstream from the outer edge of the nozzle (AIR6037, 2010).

**Hazardous Air Pollutants –** HAP's **-** 188 pollutants that the Clean Air Act Amendments of 1990 required the EPA to regulate (Essama et al., 2008).

**National Ambient Air Quality Standards –** NAAQS- The Clean Air Act, which was last amended in 1990, requires EPA to set National Ambient Air Quality Standards for wide-spread pollutants from numerous and diverse sources considered harmful to public health and the environment (Environmental Protection Agency, 2011).

**Non-road** - Mobile emission sources not commonly operated on public roadways such as airport ground support equipment, lawn mowers, etc. (Miake-Lye et al., 2008).

**Non-volatile particles** - Particles that exist at engine exit plane temperature and pressure conditions, and that do not contain volatile particle contributions that condense at lower temperatures (AIR6037, 2010, p. 43).

**Nucleation** - The process of initial formation of a particle from vapor. This process is usually facilitated by the presence of small particles called condensation nuclei, which serve as sites for condensation (Essama et al., 2008).

**Organic carbon** – OC- A major component of particulate carbon and is composed of many compounds most of which partition between the gas and aerosol phases at ambient conditions (Miake-Lye, et al., 2008).

**Particulate Matter –** PM - A mixture of microscopic solids, liquid droplets, and particles with solid and liquid components suspended in air (Miake-Lye, et al., 2008).

**PM10**, **PM2.5** - Regulatory designations of particulate matter less than or equal to 10 µm, and 2.5 µm, respectively, in diameter; these measures are similar to the terms coarse, and fine (Essama, et al., 2008).

**Primary particle -** A particle that is emitted directly from the source. (Essama, et al., 2008)

**Refractory-** Resistant to heat: non-volatile (Essama, et al., 2008).

**Secondary particle -** A particle that forms as the result of a chemical reaction or other means by combining with other elements after leaving the source. These particles form on the timescales of minutes to days and may continue to form in air masses moving hundreds of kilometers from the source (Essama, et al., 2008).

**Total carbon** - The sum of elemental carbon and organic carbon (Miake-Lye, et al., 2008).

**Transient** - A momentary or temporary variation in a variable of interest (e.g., engine power, ambient pressure, temperature) (Miake-Lye, et al., 2008).

**Condensation Particle Counter** – CPC –A continuous-flow instrument that detects particles down to 2.5 nm. It uses a special sheath-air flow design that improves response to changes in particle concentration and increases counting efficiency for ultrafine particles (TSI Inc, Model 3776 Spec Sheet, p. 1).

**Volatile particles** - Particles formed from condensable gases after the exhaust has been cooled to below engine exit conditions (AIR6037, 2010, p. 43).

## 1.6. Assumptions

The research was conducted according to the following assumptions:

- The UCPC is properly maintained and functioning properly.
- The engine in the test cell is functioning properly.
- The fine particle count is not dependent on standard day conditions.
- The engine had been ran within 7 days of the sampling

## 1.7. Limitations

The research was conducted within the following limitations:

- Test cell research only covered the F109 test cell in the Niswonger Aviation Technology Building.
- Only areas inside the F109 test cell were sampled.

- This research only covered the property within the Purdue University Airport perimeter fence.
- Test cell sampling only occurred while the engine was not operating.
- This research only measured residual particles in the test cell.
- This research only measured fine particle counts.
- This research does not record engine type, hours, or fuel type.

## 1.8. Delimitations

The research conducted was completed according to the following delimitations:

- This research did not cover any airport sites other than the Purdue University airport.
- This research did not cover any turbine engine test cells other than the F109 test cell.
- This research did not assess the exhaust emissions of any engines.
- This research did not attempt to assess any health risks.
- This research did not attempt to put any policies in place at the Niswonger Aviation Technology Building.
- This research did not attempt to characterize the mass of any particles measured.
- This research did not attempt to characterize the size distribution of the samples gathered.
- This research did not attempt to characterize the composition of the samples gathered.

- This research did not try to correlate emissions to engine type, hours, or fuel used.
- This research did not try to characterize normal airport flight operations. Samples were taken during normal weekday operations.

## 1.9. Summary

This study compared the ambient average fine particle count in the F109 test cell fueled by Jet-A at the Niswonger Aviation Technology Building to the ambient fine particle count observed at the Purdue University Airport and identified methods to reduce exposure to hazardous air pollutants.

# SECTION 2. LITERATURE REVIEW

A literature review was conducted on particulate matter, its origins, composition, how it is measured and regulated, and what its health effects are.

## 2.1. Introduction

All aircraft gas turbine engines produce incredibly small particles as a result of the combustion of the hydrocarbons in fuel. These particles can be as small as 1 nanometer, or 100,000 times smaller than a human hair in diameter. However, turbine engines are not the only contributor to the emission of particulate matter in aviation. Ground service vehicles, brake and tire wear, construction, and even passenger vehicles can contribute to PM levels at airports. Most attempts at quantifying PM did not even occur until the mid-1990’s. The Clean Air Act requires that all airports meet with standards for PM emissions in all current and proposed future operations (Miake-Lye et al., 2008). Unfortunately airports must do so with limited data available to them. Studies have shown these particles can lead to cardiovascular and respiratory trouble, especially among individuals with pre-existing conditions (Miake-Lye et al., 2008).

## 2.2. Particulate Matter

The Airport Cooperative Research Program Report 6 (2008) describes particle pollution resulting from combusting hydrocarbon is a “mixture of microscopic solids, liquid droplets, and particles with solid and liquid components suspended in air” (p. 5). These solids are referred to as non-volatiles and are primarily made of carbonaceous material, metal from engine component wear, and matter ingested into the engine (AIR6037, 2010). By definition, only nonvolatile particles exist in the conditions of the engine exit plane. However, nonvolatile particles can continue to grow through the absorption and condensation of organic and inorganic gaseous compounds (AIR6037, 2010). Liquid particles called volatile particles also form from condensing gases in the exhaust plume as they cool (AIR6037, 2010).

The organic carbon and elemental carbon ratio in the exhaust plume depends on the operating condition of the engine (AIR6037, 2010). The ratio can vary from 10% elemental carbon and 90% organic carbon at idle to 100% elemental carbon at take-off thrust settings (AIR6037, 2010). The Society of Automotive Engineers (2010) states that the amount of black carbon produced is “strongly correlated to the elemental carbon fraction of the aerosol” (AIR6037, p. 13). These particles appear black due to their ability to “absorb light in the visible spectrum region” (AIR6037, 2010, p. 13). Therefore light absorption measurement is an important method of tracing the nonvolatile portions of the exhaust.

### 2.2.1. PM Creation

Airport particle emissions are not limited to the products of aircraft jet engines. There are a variety of other vehicles and operations that lead to the production of particulate matter. Essama et al., (2008) lists the following as significant PM contributors:

- Aircraft engines
- Auxiliary power units (APU's)
- Ground service vehicles (tugs, baggage carts, etc.)
- Passenger vehicles
- Equipment wear
- Emergency response training
- Construction (p.1)

The resulting particle sizes from these sources range from course to ultrafine and are produced at different rates (Essama et al., 2008). Ultrafine particles in aircraft exhaust include several particle types ranging from those that are formed in the combustion chamber, to those that form from the nucleation of condensable gases. Ultrafines can also increase in size due to "coagulation and condensation onto the particle surfaces in the 0.1 to 0.5 μm range" (Miake-Lye, 2008, p. 6). However, the diesel particles produced by ground service vehicles such as aircraft tugs and baggage trucks are often larger than aircraft particles and, according to Miake-Lye et al., (2008), "aggregate into chain particles rather than the more spherical particles seen from aircraft engines" (p.6).

Secondary particle formation results from chemical reaction and particle nucleation. This reaction produces new particles or adds to particles already present. Essama et al., (2008) lists several examples of secondary particle formation:

- Conversion of sulfur oxides (SOx), a product of sulfur oxidation in fossil fuel to sulfuric acid vapor. This then forms droplets as the sulfuric acid nucleates due to low vapor pressure. This resultant aerosol is highly reactive and can combine with other gases to form sulfate salt particles.
- Conversion of nitrogen dioxide (NO2) to nitric acid vapor that can mix together with particulate matter in the atmosphere and also reacts with ammonia to create ammonium nitrate particles.
- Reaction of gaseous volatile organic compounds condensing into organic compounds also adds to atmospheric particulate (p. 6).

The shear variety of methods that particulate matter can be formed illustrates why the measurement of PM emissions is such a difficult undertaking. The various particles behave very differently in the atmosphere adding to the complexity of measuring and understanding them.

### 2.2.2. PM Characteristics

According to Essama et al., (2008) primary volatile PM is formed in the near-field plume, or less than one minute after it is emitted. Secondary volatile PM forms much slower and can continue to form in atmosphere miles away from the sources. The diameters of particulate matter in the atmosphere can range from 1 nm to 100 µm (Essama et al., 2008). Particles smaller than 10µm but larger than 2.5µm are defined as

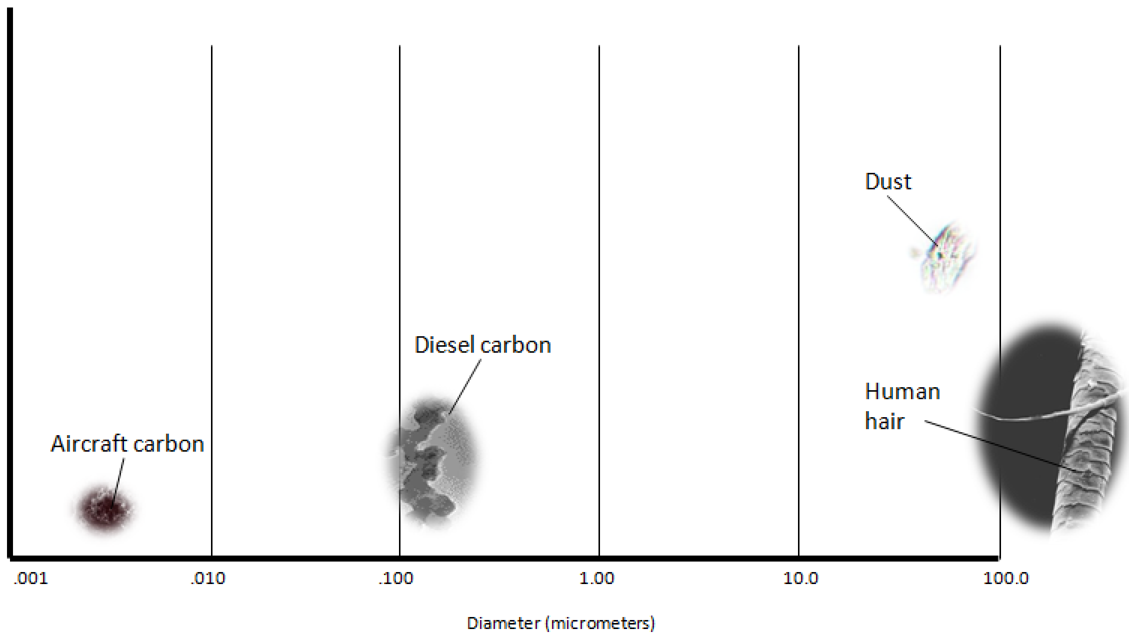



Figure 1. Particle Size Comparison (adapted from Miake-Lye et al., 2008, p. 13)

course particles (Miake-Lye et al., 2008). Those particles that are sized between 2.5 µm and .1 µm are referred to as fine particles and those smaller than .1 µm are called ultrafines (Essama et al., 2008). Dust and soot particles are usually large enough to be seen be the naked eye while other particles are so small that they require an electron microscope (Essama et al., 2008). Figure 1 illustrates how these aircraft carbon particles compare to other particles. Ultrafine particles have a relatively short lifespan, from minutes to hours, and generally travel from 1-10 miles, as they are more likely to develop into larger fine particles. Fine particles typically stay in the atmosphere longer since they do not increase in size and are too small to settle or impact on stationary surfaces (Essama et al., 2008). Karcher et al., state that atmospheric particulate has "been observed up to altitudes of 20 km" (1999, p. 1). At these altitudes, particles can affect the formation of cirrus clouds (Jensen & Toon, 1997). Fine particulate can remain in the atmosphere for days or weeks and be carried thousands of miles. Coarse particle lifetimes depend on their size, atmospheric conditions, and altitude and typically settle rapidly from the atmosphere within minutes or hours of creation. Most coarse particles are generally too large to follow air streams and tend to settle out from deposition shortly after creation (Essama et al., 2008).

## 2.3. Research

Before the 1990s, jet engine PM emissions were only classified as smoke and were quantified using the Society of Automotive Engineers (SAE) Aerospace Recommended Practice 1179—Smoke Number (SAE, 1991). Smoke Number is still in use and according to the Code of Federal Regulations, current engines are not to exceed a Smoke Number (SN) of 30 (CFR 34.30, 2011). However, the smoke number does not identify key aspects of the PM such as size and distribution and is of limited value to the analysis of environmental and health impacts of aviation emissions. As a result, new methods for characterizing PM emissions based on characteristics such as "morphology, chemical composition, distributional accounts of size and volume, or number and mass concentration" were developed (Essama et al., 2008, p. 1). These methods were first applied to quantify PM emissions for military engines (Spicer et al., 1994). The US Air Force Engineering and Services Center performed a series of tests between 1984 and 1989 (EPA, 2009). These tests were intended to analyze the composition of gaseous hydrocarbons emitted in turbine engine exhaust. This series of tests sampled five military engines. According to the EPA (2009), some of this data was used in its SPECIATE data repository. This database is used to estimate toxic emissions for commercial aircraft. This study was performed with both on-wing engines as well as engines mounted in test cells. While these methods and data improved the knowledge aircraft engine PM emissions, these studies were performed on older turbofan engines which are based on obsolete technology.

From 1997 to 2002 the USAF's Institute for Environment Safety and Occupational Risk Analysis performed a similar series of tests with a different type of jet fuel named JP-8 (EPA, 2009). In these tests, a variety of engine types were used including turbofans, turbojets, turboprops, and a turbo shaft engine. These tests are called the Gerstle dataset (EPA, 2009). The goal of these tests was to characterize the exhaust emissions of the engine types mentioned earlier.

NASA sponsored the Experiment to Characterize Aircraft Volatile Aerosol and Trace-Species Emissions, or EXCAVATE test initiative in 2002 (EPA, 2009). For this test, a Boeing 757 with two RB211-535-E4 engines was tested on the ground to investigate aerosol production when compared to engine power settings, fuel composition and age of the exhaust plume (EPA, 2009).

The next series of tests was a cooperative effort between the Department of Defense, EPA, FAA, and NASA (EPA, 2009). This series of tests was known as the Aircraft Particle Emissions Experiment (APEX). These tests were the first to examine both gaseous and particulate emissions of commercial aircraft engines and investigated the effects of varying engine thrust on emissions using the ICAO Landing-Takeoff Cycle standard described in ICAO Annex 16. Additionally, this testing gathered data on emissions at airports and effects of varying fuel compositions by altering sulfur content (EPA, 2009). The APEX tests created one the “most extensive set of gaseous and particulate emissions data from in-service commercial engines”, according to the EPA (2009, p. 9). The next three sections describe each of the APEX tests in more detail.

### 2.3.1 APEX 1

The initial APEX tests, APEX1 began April, 2004 at Edwards Air Force Base in California. A NASA DC-8 was used for on ground testing. Sample rakes were set up at 1 m, 10m, and 30m intervals in the exhaust plume and samples taken and a variety of thrust settings (EPA, 2009). Essama et al., discusses the “specific objectives were to – examine the impact of fuel sulfur and aromatic content on non-volatile (soot) and volatile particle formation; follow the evolution of particle characteristics and chemical composition within the engine exhaust plume as it cooled and mixed with background air; examine the spatial variation of particle properties across the exhaust plume; evaluate new measurement and sampling techniques for characterizing aircraft particle and gas emissions; and provide a dataset for use in studies to model the impact of aircraft emissions on local air quality" (2008, p. 12).

A second APEX test was performed at the Hartsfield-Jackson Atlanta International Airport. This test consisted of two different portions: one at the maintenance facilities of Delta Airlines and was geared towards PM emissions around the exhaust nozzle (Essama et al., 2008). Part two of the study focused on sampling PM emissions generated during normal airport operations. Mobile laboratory stations were positioned next to active runways to sample emissions from air traffic. These measured emissions from advected exhaust generated by normal airport traffic landing, taxiing and takeoffs (Essama et al., 2008).

APEX1 focused on the particle size distributions and particle number and mass of particles produced per kilogram of fuel burned (Essama et al., 2008). As stated in ACRP Report 9, engine exhaust PM was found to vary in composition and as the plume ages (Essama et al., 2008). The PM sampled was found to contain both volatile and non-volatile particles based on where the sampling site was located. The APEX1 study came to several conclusions on non-volatile particles:

- "Non-volatile particles range from 10 to 300 nanometers.
- Average diameter increased with thrust going from 15 nanometers to 40 nanometers at take off.
- Non-volatile PM parameters did not vary for the fuels tested.

- Non-volatile PM parameters did not depend on plume age, or distance downstream from the exhaust nozzle, indicating that black carbon does not change as plume ages.
- Number-based Emission Index (EIn) was found to be highest at takeoff thrust, with a smaller peak at idle and smallest levels related to approach thrust levels
- EIn at low thrust levels decreased during the first couple hours of engine time. EIn also decreased as ambient air temperature increased.
- The mass-based Emission Index (EIm) increased with thrust." (Essama et al., 2008, p. 21)

Additionally, APEX1 observed that the samples which were collected downstream often contained high concentrations of volatile particles containing material that is in gaseous form at temperatures in above 572 degrees F (Essama et al., 2008). However, these particles were not observed to be present in the vicinity of the exhaust nozzle. EIn was found to be noticeably larger downstream at low thrust levels than observed at the exhaust nozzle as well (Essama et al., 2008).

### 2.3.2 APEX 2

APEX2 testing took place in Oakland, California in August 2005 and specifically developed emission factors for PM10 chemical profiles (EPA, 2009). APEX2 was conducted similarly to the Atlanta-Hartsfield tests in that the first tests were also performed in the exhaust nozzle area and the second portion focused on airport operational traffic (EPA, 2009). These tests relied heavily on knowledge gained from the prior APEX studies. Exhaust was sampled directly from the combustor section and transported via sample line running to lab instruments. Readings were taken with the engines running at six different thrust settings (Essama et al., 2008). The second portion of testing similarly consisted of mobile sampling stations setup along the active runways monitoring aircraft in the standard LTO cycle (Essama et al., 2008). From 7am to 7pm, samples were taken from the vicinity of the runway. This test also recorded aircraft tail numbers and status; i.e. which portion of the LTO cycle they were operating in. Then by correlating the tail numbers to airframes, an operational distribution of the aircraft was created.

APEX2 found that most observations are consistent with the data gathered in previous APEX studies. APEX2 also concluded that as the exhaust plume expands and interacts with the ambient air, a large number of small particles are produced. These nucleates are not present at the exhaust nozzle. Essama et al., note the production of small particles in the exhaust plume increases EIn by an order of magnitude when compared to those present at the exhaust nozzle (2008).

### 2.3.3 APEX 3

APEX3 took place in Cleveland, Ohio in fall 2005 with the goal of further developing emission factors for PM10 and chemical profiles of current engines, to determine fuel property and engine operation effects on PM10 emissions, and investigate Smoke Number and mass emission rates (EPA, 2009). Similar in nature to the previous APEX studies, one half was conducted on the exhaust nozzle and near-field plume area of stationary engines and the other half on local airport operations. This study is the most recent one and as such the data analysis is not available yet (Essama et al., 2008).

2.4. PM Sampling Methods

Jalbert and Zaccardi state that turbine engine emissions test protocols were originally developed in the 1960's (2002). The guidelines for particle sampling are established in the Society of Automotive Engineers Aerospace Information Report AIR-6037. Particle number concentration is the number of particles per unit of volume, usually expressed in $cm^3$. Studies have shown that Particle Number increases as a function of engine power (Cheng, 2009). Burtscher (2005) mentions that number concentration is almost exclusively measured by Condensation Particle Counters.

There are a variety of systems used to sample aerosol particulate. Condensation Nuclei Counters (CNC's) have been used as particle counters for over a century. CNC's operate by "growing small particles into the size range suitable for easy optical detection utilizing condensation of supersaturated vapors onto the particles" (AIR6037, 2010, p. 49). CNC's fall into two types: expansion-type and constant pressure systems. Constant Pressure Systems are more popular due to their continuous-flow measurement capability (AIR6037, 2010). Appendix H illustrates the path the sample takes once in the machine. Sample air is inducted through an inlet tube where some form of alcohol, typically butanol, evaporates into the stream (AIR5892, 2007). Once the sample enters the condenser, the sample air gets super-saturated by cooling or heating the tube walls. This condenses the vapor onto the sample particles to create droplets large enough to be analyzed by the optical detection cell (AIR6037, 2010). Brock states that super saturation can be controlled by, “varying the geometry, temperature, and/or flow rate of the condenser and/or by changing the working fluid” (2000, pp. 26,556). Once in the optical detection cell, the droplets are illuminated and light scattered by the droplets is detected by a photodetector. The photodetector then converts the scattered light into an electrical pulse that is recorded as the particle count (AIR6037, 2010).

## 2.5. Regulation

Aircraft engine emission standards apply at the engine exit, yet PM of concern to regulators and the community is not fully formed at that point. Coarse, fine, and ultrafine particles typically exhibit different behaviors in the atmosphere. As discussed in AIR-6037, the European Commission is implementing new PM legislation for light passenger and commercial vehicles (2010). There are several regulatory provisions planned for environmental purposes that apply to airport operations and associated vehicles. ACRP 6 states that “aircraft engines have certification requirements for smoke emissions; ground access vehicles are subject to tailpipe emission standards; the composition of jet fuel, diesel fuel, and gasoline is regulated to limit harmful emissions; many operational activities and equipment require operating permits; and airport construction and expansion plans are subject to constraints where the regional air quality does not meet healthy standards” (Miake-Lye et al., 2008, p. 7).

The EPA is responsible for the majority of emissions regulation, which is then administered locally by state agencies. In 1971, the EPA established the first National Ambient Air Quality Standards (NAAQS) for particulate matter (Miake-Lye, 2008). Brown et al., state that the NAAQS were in fact “recently tightened “(2008, p. 3). These standards were revised in 1987 when it transitioned from the prior Total Suspended Particles (TSP) standard to the new PM10 standard (Miake-Lye, 2008). ACRP 9 adds that in 1997, the PM2.5 standard supplemented the existing PM10 standard (Essama et al., 2008). The EPA no longer regulates particulate exceeding 10 µm like ash and dust since they are not considered “readily inhalable” (Miake-Lye, 2008). However, according to ACRP 9, recent studies indicate that PM2.5 cannot be used as a substitute for ultrafine particles, so future regulations may adopt PM1.0 as the new standard (Essama et al., 2008).

The EPA typically sets its ambient air quality standards for regions representing major metropolitan areas. As stated in ACRP 6, “ the annual average background for PM10 ranges from 4 to 8 µg/m3 in the western United States and 5 to 11 µg/m3 in the eastern United States; for PM2.5, estimates range from 1 to 4 µg/m3 in the west to 2 to 5 µg/m3 in the east” (Miake-Lye, 2008, p. 8).

## 2.6. Health Impacts

It is well recognized that the operation of an airport has a potentially major impact on the health of people living or working in its vicinity (Johnson et al., 2008). Exposure to fine and ultrafine particulate may be related to early death from heart or lung disease (Miake-Lye, 2008). Fine and ultrafine particles can exacerbate heart and lung conditions and have been linked cardiovascular problems, cardiac arrhythmia, cardiac arrest, respiratory problems, asthma attacks, and bronchitis (Miake-Lye, 2008). Brown et al. (2008), suggest that out of all health impacts associated with aviation, half were due to secondary PM, with up to 38% deriving from primary PM (2008, p. 6.). Individuals that suffer from pre-existing cardiac or respiratory conditions, especially older adults, and children are particularly susceptible.

## 2.7 Summary

Particle matter emissions are becoming a vital area of research for aviation. There are two kinds of PM, volatile and non-volatile. PM is a product of engine combustion as well as nucleation of gaseous particles in the exhaust plume. Aircraft engines are not the only contributor to PM emissions. Ground service engines, tire and brake wear, and construction are among the other factors that lead to PM. These particles can get as small as one nanometer in diameter and travel in the atmosphere for hundreds of miles. Due to their extremely small size, PM have the potential to be harmful to health, specifically causing respiratory and cardiac issues. PM used to be identified by SAE Smoke Number, but recent research efforts have begun classifying PM in terms of mass, number, and composition. The APEX series of studies have improved the quantification of exhaust emissions. Due to the findings of these and other studies, new regulations are being implemented around the world to limit PM emissions.

# SECTION 3. METHODOLOGY

This research was an observational study to determine the impact a turbine engine test cell's presence has on airborne nanoparticle counts when compared to the ambient particle counts on the surrounding airport property. This section outlines the process that was carried out to sample the residual particle concentrations in the test cell and the runway, and analyze the differences in average particle concentration to determine of a test cell impacts local air quality.

## 3.1. Population and Data Collection

Air samples were taken at two sites with a Condensation Particle Counter. The first sampling location was inside the F109 turbofan engine test cell located in the Niswonger Aviation Technology Building at Purdue University. This test cell is used to teach fundamentals of aviation powerplant technology as well as the National Test Facility for Aerospace Fuels and Propulsion to test alternative aviation fuels. The second test site was located adjacent to the runways of Purdue University Airport (KLAF). The samples were taken during normal airport operations.

## 3.2 Sampling and Instrumentation

The sampling was accomplished using a TSI Inc. Model 3776 Ultrafine Condensation Particle Counter. This machine is capable of measuring particle sizes down to 2.5 nanometers and is designed for combustion and engine exhaust research. It also features a filter that filters 93% of impurities down to .01 microns. The sampling device was placed in the test cell adjacent to the engine thrust stand in the test cell as shown in Figure 2. During the test cell sampling sessions, the engine was not operating.

Figure 2. Condensation Particle Counter in the F109 Test Cell

During sampling the CPC was connected to a Hewlett-Packard G70 laptop computer to run the Aerosol Information Manager (AIM) software, a copyright of TSI Inc. The AIM program allows the user to schedule the CPC to automatically schedule and sample remotely as shown in Figure 3. AIM stores the data gathered in the sampling sessions. In addition, the AIM software graphically displays the particle count in real time as the sample is in progress as expressed in Figure 4. Samples were taken in four separate sessions throughout March, April, and May 2011.

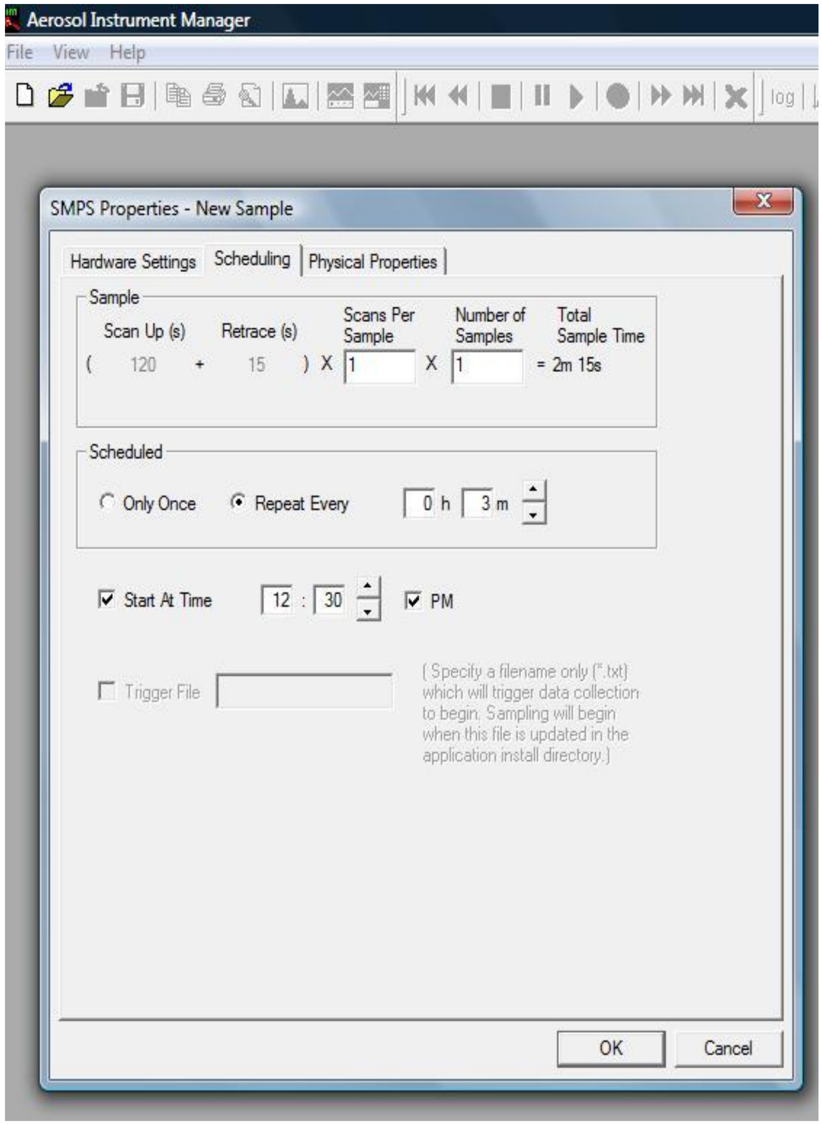



Figure 3. Sample Scheduling

During each sampling session 25-26 samples were taken, with samples scheduled every three minutes. Each sample session lasted approximately one hour and thirty minutes. Normal airport operations were still in progress during sampling. A PT6 test cell is located adjacent to the F109 test cell.

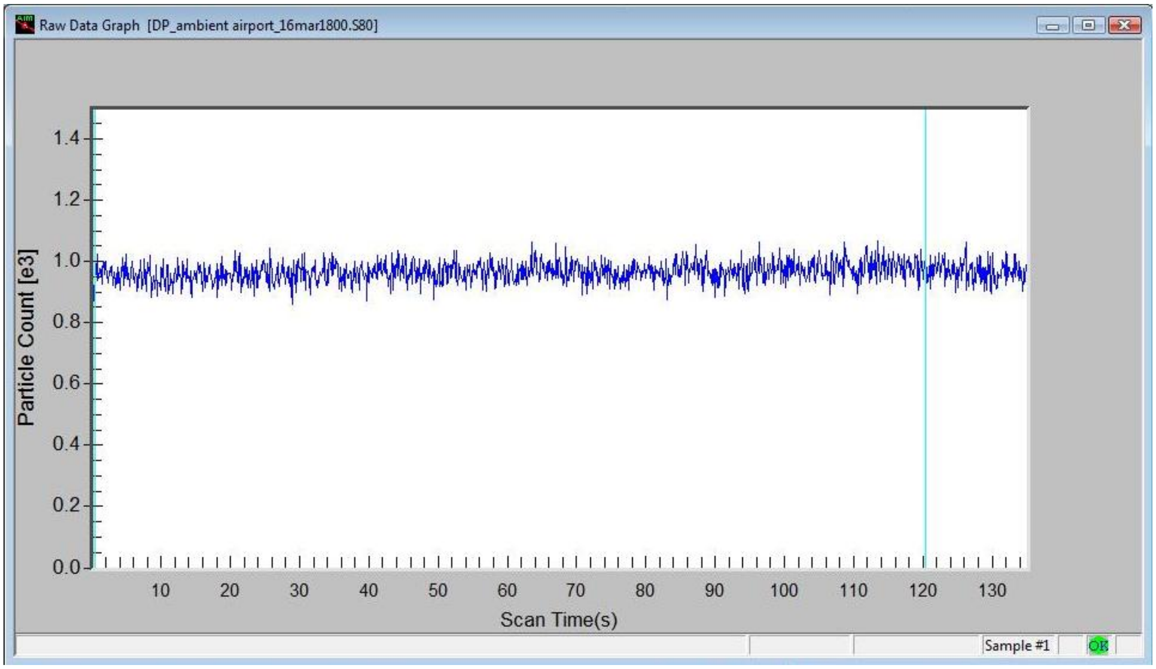



Figure 4. Real-Time Sampling Display from TSI Model 3776 UCPC

The test cell sample sessions in this study were:

- Session 1, 9 MAR 2011, 3:00 pm: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- Session 2, 16 MAR 2011, 4:30 pm: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- Session 3, 17 MAR 2011, 2:00 pm: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- Session 4 23 MAR 2011, 9:00 am: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- TOTAL: 135,000 samples.

The second sampling site was located next to the taxiway and runway at Purdue University Airport. Figure 5 illustrates the sample location. The setup up and peripheral equipment were identical to procedures utilized in the test cell sampling sessions. Since these portions of the research were undertaken at an operational airport, general aviation and other aircraft conducted normal operations such as landing, takeoff and taxiing. Flights typically consist of small piston engine aircraft, such as the Cirrus SR20.

Figure 5. External Airport Sample Site

The airport sampling location is displayed in Figure 6. This site was chosen for a variety of reasons. Electrical outlet access was a critical requirement for this research due to the power needs of the CPC. This site was also selected to limit unnecessary transport of the equipment from storage to sample site due to the machine's sensitivity to movement. This site also was unobtrusive and did not interfere with normal operations.

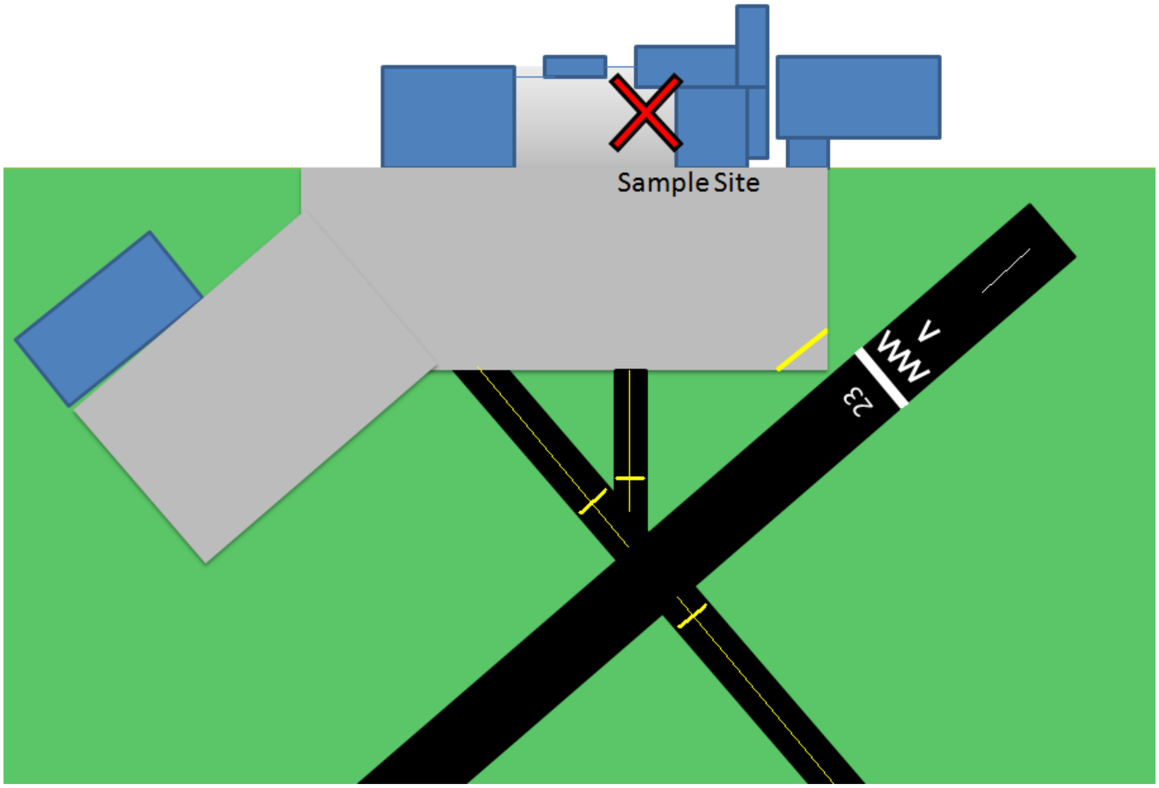



Figure 6. Airport Ambient Sampling Location

The airport sample sessions were:

- Session 1, 16 MAR 2011, 6:00 pm: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- Session 2, 17 MAR 2011, 3:30 PM: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- Session 3 1 APR 2011, 8:00 am: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- Session 4 13 MAY 2011, 12:00 pm: 25 samples gathered. 1,350 individual measurements per sample. 33,750 samples total.
- TOTAL: 135,000 samples.

### 3.3 <u>Analysis</u>

After the data was collected, it was separated into two populations: the samples gathered in the test cell and the gathered on the airport ramp. From these samples, in order to eliminate the effect of external events on the samples, segments were taken where the samples had stabilized. Twenty 15-second segments were selected to condition the data against outside influence. From these fields, the average was then taken of the particle count for the fifteen second segment. Five random numbers from 1-20 were then generated to select five random sections of this population. A two sample t-test was then applied to these random samples to compare the means. This analysis is presented in Section 4.

### 3.4 <u>Summary</u>

This research was conducted to investigate the possible differences in ambient particle counts associated with a turbine engine test cell and the airport property. It was conducted by sampling residual PM in the atmosphere of the two locations and comparing them statistically.

## SECTION 4. DATA AND RESULTS

All data gathered is only applicable to Purdue University Airport. The statistical analysis performed on the data gathered was performed using Minitab software. This statistical analysis was conducted to test the hypothesis that the average particle count was significantly larger in the test cell than that present on the airport property. This leads the null and alternate hypotheses to be as follows:

- Ho: μ-test cell = μ-airport
- Ha: μ-test cell > μ-airport

A two sample t-test was applied to the sample data to compare the true means. The two sample t-test was selected due to its appropriateness when comparing true means of large populations where the true standard deviation is not known.

### 4.1 Data

The data is displayed graphically and numerically in the AIM software. Figures 4 and 6 illustrate the data presented in the AIM software interface.

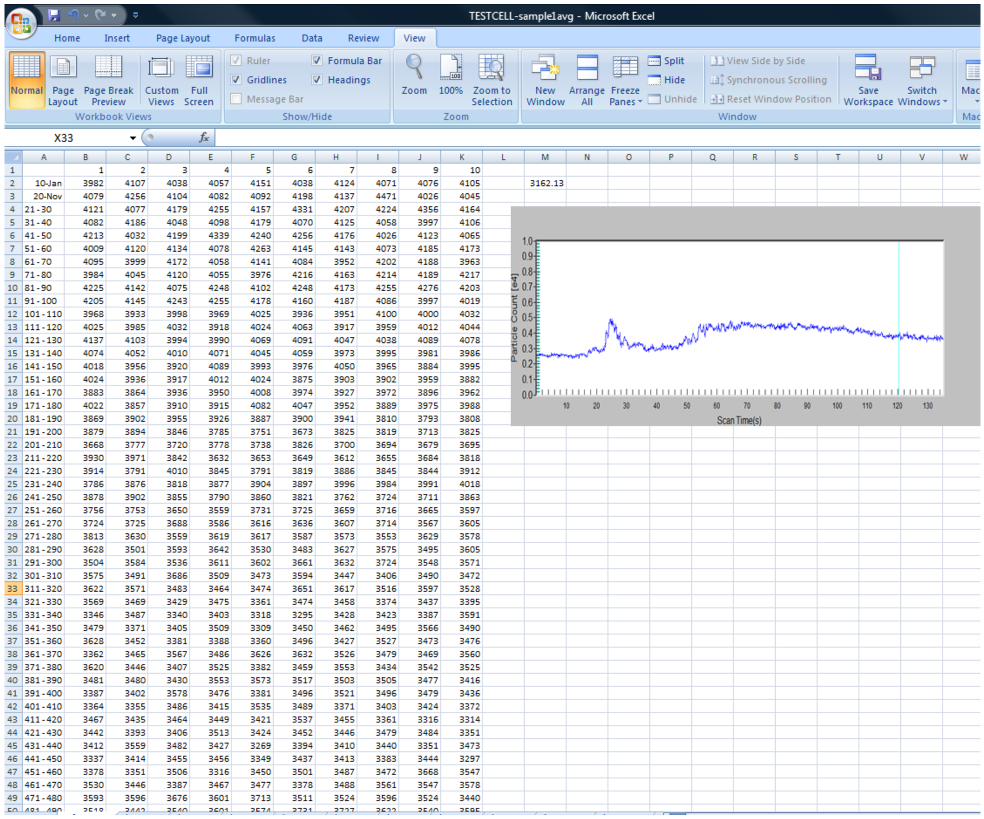
Raw Data Table [DP_ambient airport_16mar1800.S80]

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 - 10 | 902 | 923 | 872 | 959 | 947 | 965 | 1024 | 938 | 947 | 947 |
| 11 - 20 | 977 | 962 | 975 | 928 | 980 | 993 | 1001 | 959 | 998 | 1001 |
| 21 - 30 | 946 | 965 | 932 | 945 | 959 | 981 | 966 | 985 | 971 | 935 |
| 31 - 40 | 923 | 966 | 935 | 913 | 934 | 960 | 929 | 982 | 952 | 905 |
| 41 - 50 | 941 | 949 | 953 | 1011 | 922 | 972 | 997 | 947 | 955 | 1024 |
| 51 - 60 | 942 | 952 | 960 | 924 | 920 | 965 | 962 | 999 | 956 | 950 |
| 61 - 70 | 932 | 942 | 963 | 942 | 902 | 924 | 943 | 972 | 946 | 1004 |
| 71 - 80 | 935 | 911 | 936 | 922 | 966 | 1007 | 947 | 902 | 936 | 996 |
| 81 - 90 | 962 | 983 | 952 | 1022 | 883 | 908 | 917 | 906 | 955 | 909 |
| 91 - 100 | 932 | 949 | 988 | 889 | 939 | 929 | 925 | 932 | 908 | 980 |
| 101 - 110 | 948 | 1008 | 960 | 930 | 919 | 923 | 903 | 987 | 990 | 895 |
| 111 - 120 | 915 | 924 | 924 | 960 | 929 | 933 | 893 | 963 | 948 | 979 |
| 121 - 130 | 942 | 935 | 942 | 1014 | 961 | 954 | 959 | 942 | 893 | 924 |
| 131 - 140 | 1000 | 983 | 948 | 958 | 977 | 933 | 1008 | 944 | 951 | 955 |
| 141 - 150 | 934 | 968 | 908 | 882 | 931 | 950 | 953 | 968 | 943 | 960 |
| 151 - 160 | 929 | 944 | 996 | 982 | 962 | 967 | 988 | 948 | 951 | 904 |
| 161 - 170 | 969 | 996 | 916 | 979 | 933 | 938 | 934 | 972 | 974 | 989 |
| 171 - 180 | 965 | 956 | 926 | 910 | 919 | 928 | 931 | 946 | 944 | 993 |
| 181 - 190 | 884 | 933 | 973 | 938 | 951 | 971 | 1015 | 922 | 986 | 945 |
| 191 - 200 | 956 | 922 | 973 | 930 | 971 | 958 | 962 | 962 | 960 | 945 |
| 201 - 210 | 941 | 908 | 956 | 954 | 968 | 1035 | 975 | 967 | 1001 | 935 |
| 211 - 220 | 930 | 1008 | 1027 | 954 | 988 | 899 | 935 | 951 | 930 | 954 |
| 221 - 230 | 982 | 971 | 926 | 980 | 937 | 914 | 970 | 970 | 913 | 958 |
| 231 - 240 | 994 | 978 | 967 | 888 | 968 | 960 | 1003 | 916 | 915 | 968 |
| 241 - 250 | 943 | 945 | 949 | 987 | 968 | 1000 | 975 | 1006 | 977 | 991 |
| 251 - 260 | 933 | 966 | 930 | 991 | 925 | 902 | 1044 | 982 | 994 | 970 |
| 261 - 270 | 938 | 917 | 919 | 911 | 956 | 942 | 970 | 997 | 940 | 920 |

Sample #1 OK

Figure 7. Raw Data Counts Display in the AIM Software

Once the data acquisition was completed, the data was compiled by sample session in Microsoft Excel. Each sample session consisted of 25 worksheets that appeared as shown in Figure 7. Due to the large amount of data gathered, only a representative sample is displayed in Appendix A.




| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 2 | 10-Jan | 3982 | 4107 | 4038 | 4057 | 4151 | 4038 | 4124 | 4071 | 4076 | 4105 |
| 3 | 20-Nov | 4079 | 4256 | 4104 | 4082 | 4092 | 4198 | 4137 | 4471 | 4026 | 4045 |
| 4 | 21 - 30 | 4121 | 4077 | 4179 | 4255 | 4157 | 4331 | 4207 | 4224 | 4356 | 4164 |
| 5 | 31 - 40 | 4082 | 4186 | 4048 | 4098 | 4179 | 4070 | 4125 | 4058 | 3997 | 4106 |
| 6 | 41 - 50 | 4213 | 4032 | 4199 | 4339 | 4240 | 4256 | 4176 | 4026 | 4123 | 4065 |
| 7 | 51 - 60 | 4009 | 4120 | 4134 | 4078 | 4263 | 4145 | 4143 | 4073 | 4185 | 4173 |
| 8 | 61 - 70 | 4095 | 3999 | 4172 | 4058 | 4141 | 4084 | 3952 | 4202 | 4188 | 3963 |
| 9 | 71 - 80 | 3984 | 4045 | 4120 | 4055 | 3976 | 4216 | 4163 | 4214 | 4189 | 4217 |
| 10 | 81 - 90 | 4225 | 4142 | 4075 | 4248 | 4102 | 4248 | 4173 | 4255 | 4276 | 4203 |
| 11 | 91 - 100 | 4205 | 4145 | 4243 | 4255 | 4178 | 4160 | 4187 | 4086 | 3997 | 4019 |
| 12 | 101 - 110 | 3968 | 3933 | 3998 | 3969 | 4025 | 3936 | 3951 | 4100 | 4000 | 4032 |
| 13 | 111 - 120 | 4025 | 3985 | 4032 | 3918 | 4024 | 4063 | 3917 | 3959 | 4012 | 4044 |
| 14 | 121 - 130 | 4137 | 4103 | 3994 | 3990 | 4069 | 4091 | 4047 | 4038 | 4089 | 4078 |
| 15 | 131 - 140 | 4074 | 4052 | 4010 | 4071 | 4045 | 4059 | 3973 | 3995 | 3981 | 3986 |
| 16 | 141 - 150 | 4018 | 3956 | 3920 | 4089 | 3993 | 3976 | 4050 | 3965 | 3884 | 3995 |
| 17 | 151 - 160 | 4024 | 3936 | 3917 | 4012 | 4024 | 3875 | 3903 | 3902 | 3959 | 3882 |
| 18 | 161 - 170 | 3883 | 3864 | 3936 | 3950 | 4008 | 3974 | 3927 | 3972 | 3896 | 3962 |
| 19 | 171 - 180 | 4022 | 3857 | 3910 | 3915 | 4082 | 4047 | 3952 | 3889 | 3975 | 3988 |
| 20 | 181 - 190 | 3869 | 3902 | 3955 | 3926 | 3887 | 3900 | 3941 | 3810 | 3793 | 3808 |
| 21 | 191 - 200 | 3879 | 3894 | 3846 | 3785 | 3751 | 3673 | 3825 | 3819 | 3713 | 3825 |
| 22 | 201 - 210 | 3668 | 3777 | 3720 | 3778 | 3738 | 3826 | 3700 | 3694 | 3679 | 3695 |
| 23 | 211 - 220 | 3930 | 3971 | 3842 | 3632 | 3653 | 3649 | 3612 | 3655 | 3684 | 3818 |
| 24 | 221 - 230 | 3914 | 3791 | 4010 | 3845 | 3791 | 3819 | 3886 | 3845 | 3844 | 3912 |
| 25 | 231 - 240 | 3786 | 3876 | 3818 | 3877 | 3904 | 3897 | 3996 | 3984 | 3991 | 4018 |
| 26 | 241 - 250 | 3878 | 3902 | 3855 | 3790 | 3860 | 3821 | 3762 | 3724 | 3711 | 3863 |
| 27 | 251 - 260 | 3756 | 3753 | 3650 | 3559 | 3731 | 3725 | 3659 | 3716 | 3665 | 3597 |
| 28 | 261 - 270 | 3724 | 3725 | 3688 | 3586 | 3616 | 3636 | 3607 | 3714 | 3567 | 3605 |
| 29 | 271 - 280 | 3813 | 3630 | 3559 | 3619 | 3617 | 3587 | 3573 | 3553 | 3629 | 3578 |
| 30 | 281 - 290 | 3628 | 3501 | 3593 | 3642 | 3530 | 3483 | 3627 | 3575 | 3495 | 3605 |
| 31 | 291 - 300 | 3504 | 3584 | 3536 | 3611 | 3602 | 3661 | 3632 | 3724 | 3548 | 3571 |
| 32 | 301 - 310 | 3575 | 3491 | 3686 | 3509 | 3473 | 3594 | 3447 | 3406 | 3490 | 3472 |
| 33 | 311 - 320 | 3622 | 3571 | 3483 | 3464 | 3474 | 3651 | 3617 | 3516 | 3597 | 3528 |
| 34 | 321 - 330 | 3569 | 3469 | 3429 | 3475 | 3361 | 3474 | 3458 | 3374 | 3437 | 3395 |
| 35 | 331 - 340 | 3346 | 3487 | 3340 | 3403 | 3318 | 3295 | 3428 | 3423 | 3387 | 3591 |
| 36 | 341 - 350 | 3479 | 3371 | 3405 | 3509 | 3309 | 3450 | 3462 | 3495 | 3566 | 3490 |
| 37 | 351 - 360 | 3628 | 3452 | 3381 | 3388 | 3360 | 3496 | 3427 | 3527 | 3473 | 3476 |
| 38 | 361 - 370 | 3362 | 3465 | 3567 | 3486 | 3626 | 3632 | 3526 | 3479 | 3469 | 3560 |
| 39 | 371 - 380 | 3620 | 3446 | 3407 | 3525 | 3382 | 3459 | 3553 | 3434 | 3542 | 3525 |
| 40 | 381 - 390 | 3481 | 3480 | 3430 | 3553 | 3573 | 3517 | 3503 | 3505 | 3477 | 3416 |
| 41 | 391 - 400 | 3387 | 3402 | 3578 | 3476 | 3381 | 3496 | 3521 | 3496 | 3479 | 3436 |
| 42 | 401 - 410 | 3364 | 3355 | 3486 | 3415 | 3535 | 3489 | 3371 | 3403 | 3424 | 3372 |
| 43 | 411 - 420 | 3467 | 3435 | 3464 | 3449 | 3421 | 3537 | 3455 | 3361 | 3316 | 3314 |
| 44 | 421 - 430 | 3442 | 3393 | 3406 | 3513 | 3424 | 3452 | 3446 | 3479 | 3484 | 3351 |
| 45 | 431 - 440 | 3412 | 3559 | 3482 | 3427 | 3269 | 3394 | 3410 | 3440 | 3351 | 3473 |
| 46 | 441 - 450 | 3337 | 3414 | 3455 | 3456 | 3349 | 3437 | 3413 | 3383 | 3444 | 3297 |
| 47 | 451 - 460 | 3378 | 3351 | 3506 | 3316 | 3450 | 3501 | 3487 | 3472 | 3668 | 3547 |
| 48 | 461 - 470 | 3530 | 3446 | 3387 | 3467 | 3477 | 3378 | 3488 | 3561 | 3547 | 3578 |
| 49 | 471 - 480 | 3593 | 3596 | 3676 | 3601 | 3713 | 3511 | 3524 | 3596 | 3524 | 3440 |

Figure 8. Excel Data Compilation

After the data compilation was finished the sample data for all data gathered in the test cell and airport property, respectively, were aggregated into two columns in Minitab to represent the population groups. Figure 9 displays a back-to-back boxplot of both samples.

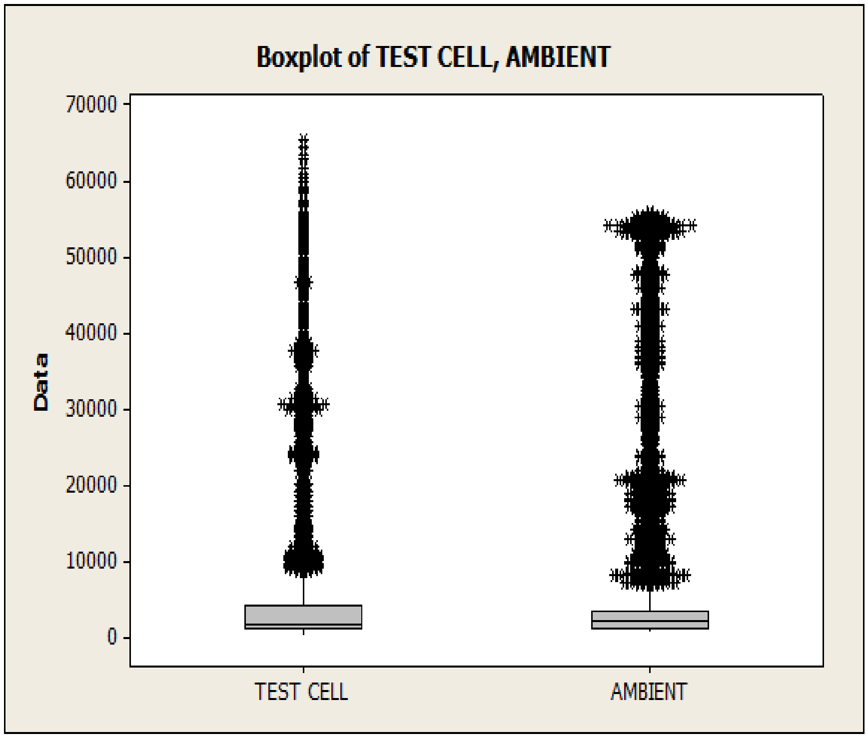



Figure 9. Test Cell and Airport Ambient Populations, with Outliers

For Figure 9 the following descriptive statistics were generated:

- Test Cell Particle Counts-
  - Range from 177-8615
  - Q1-1131
  - Median- 1826
  - Q3- 4125
  - IQR- 2994
  - Mean- 3258.1
  - Standard Deviation- 4781.2

- Airport Ambient Particle Counts-
    - Range from 714-6945
    - Q1-1330
    - Median- 2305
    - Q3- 3576
    - IQR- 2246
    - Mean- 5597.5
    - Standard Deviation- 10668.1

Each column consisted of 135,000 samples each.

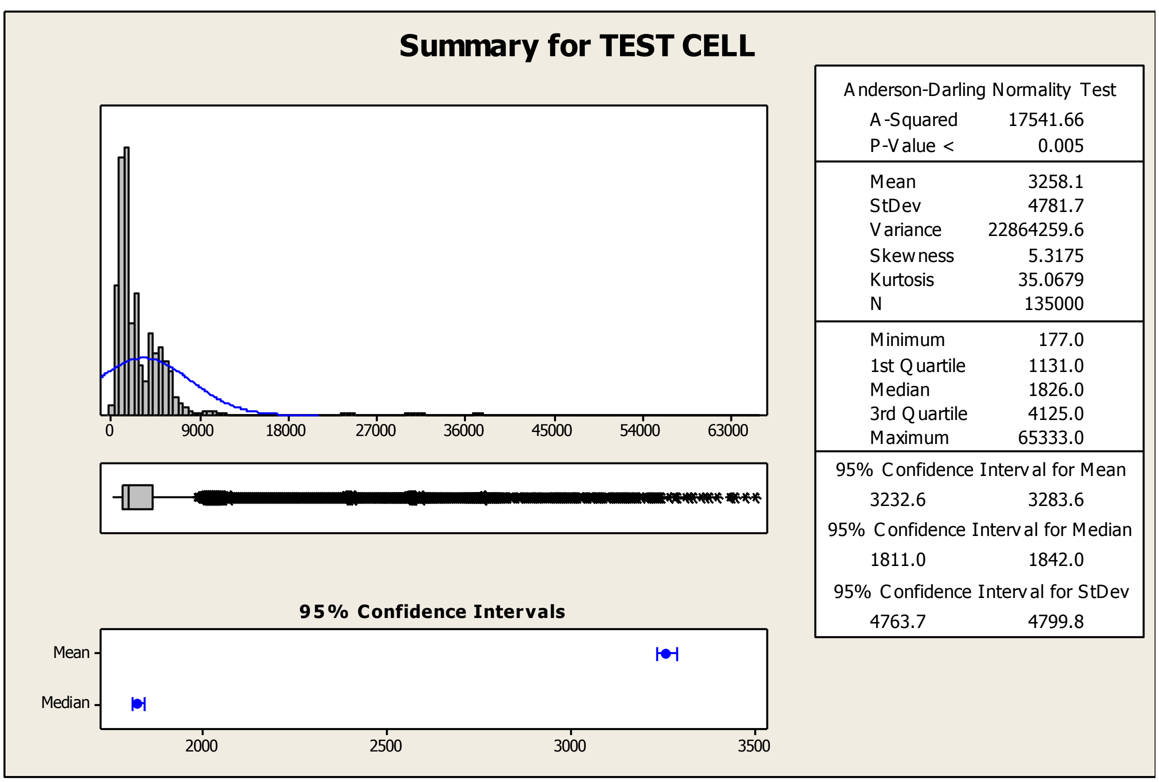



Figure 10. Test Cell Population Graphical Summary

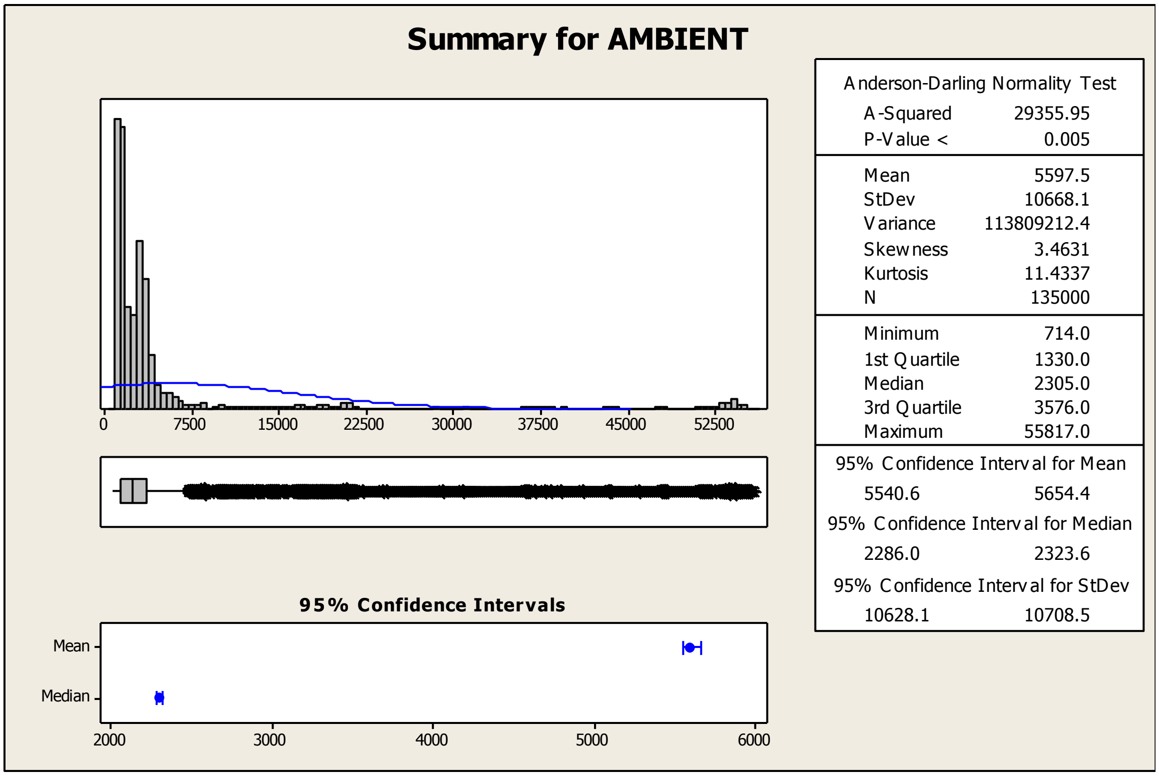



Figure 11. Ambient Airport Population Graphical Summary

### 4.1.1 Random Sampling

Simple random samples of five samples were drawn from each of the two sample sets. A back to back boxplot for this simple random sample was then created, and denoted outliers within the dataset as shown in Figure 12. These random samples were used in a two sample t-test to compare means of the particle counts in the test cell and at the airport. Table 1 illustrates the data results of the t-test in Minitab.

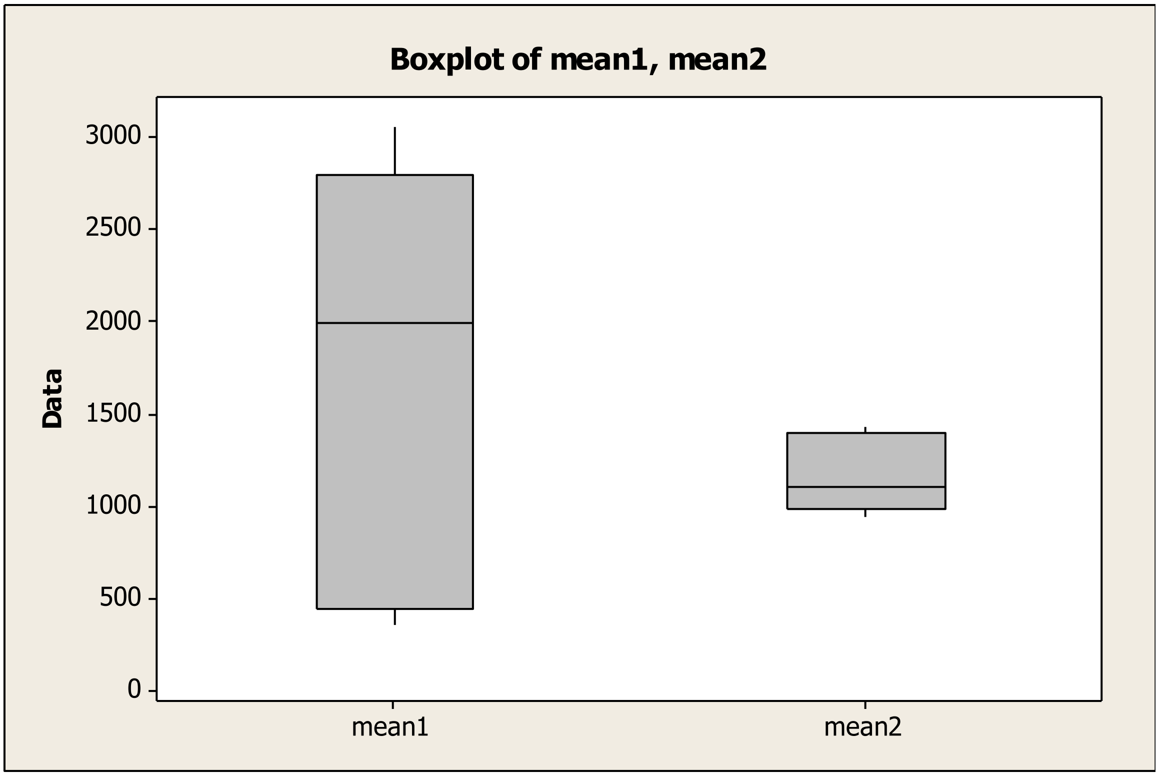



Figure 12. Random Sample Boxplot

The descriptive statistics generated for the simple random samples are shown in Figures 13 and 14.

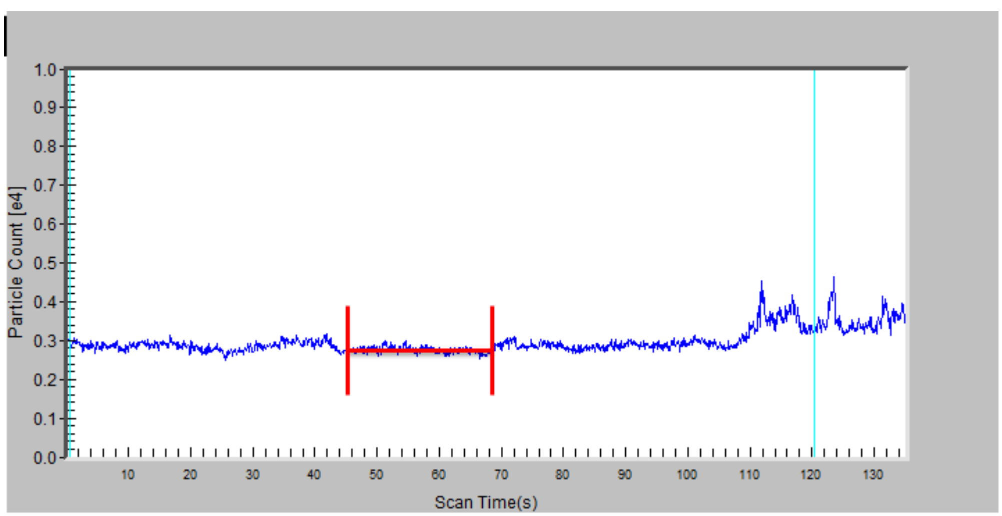



Figure 13. Stable Sample Segment

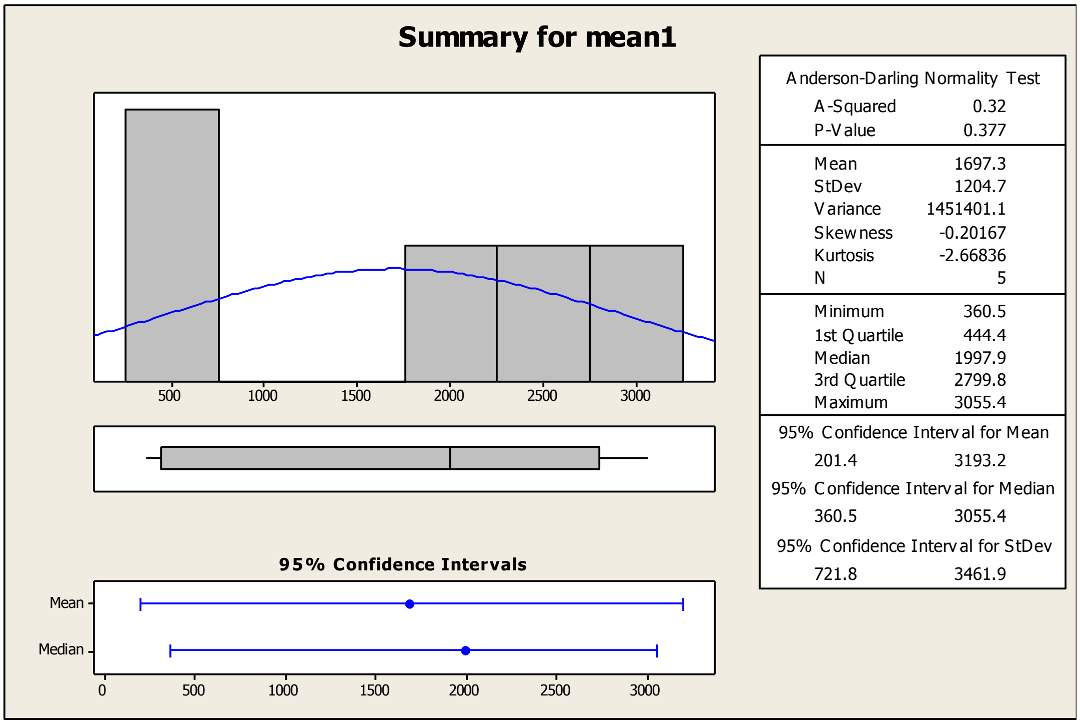



Figure 14. Descriptive Statistics for Test Cell Random Sample

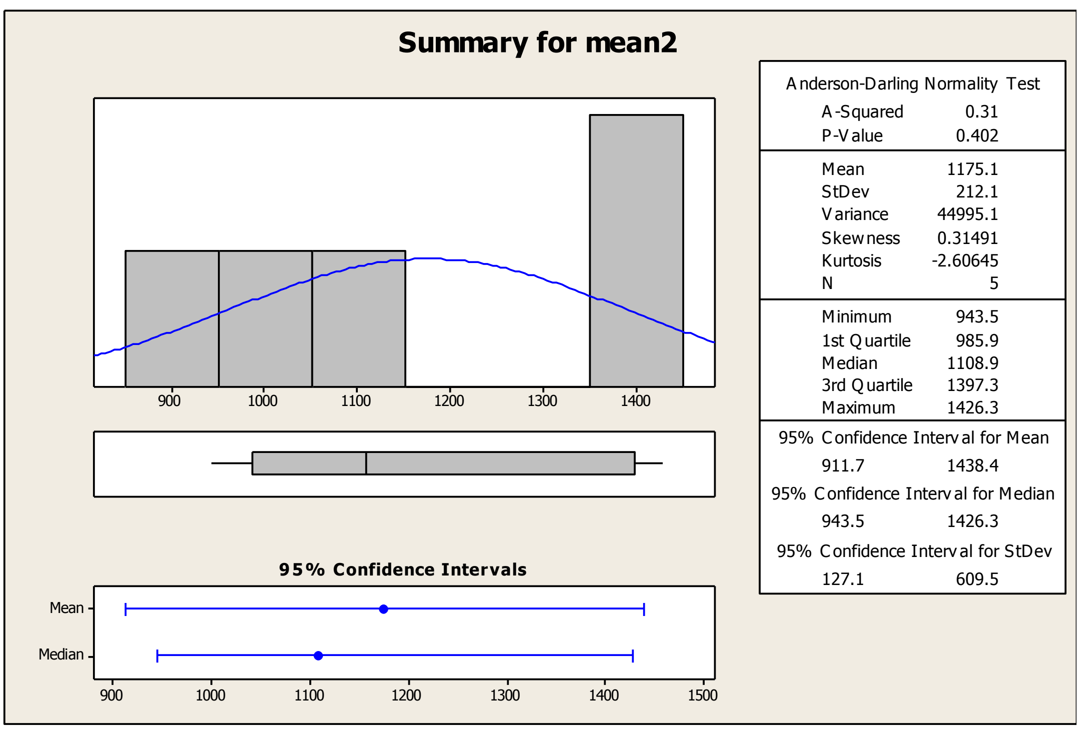



Figure 15. Descriptive Statistics for Ambient Airport Random Sample

Table 1. T-Test Results

**Two-Sample T-Test and CI: mean1, mean2**

```
Two-sample T for mean1 vs mean2

       N  Mean  StDev  SE Mean
mean1  5  1697   1205      539
mean2  5  1175    212       95


Difference = mu (mean1) - mu (mean2)
Estimate for difference:  522
95% CI for difference:  (-997, 2041)
T-Test of difference = 0 (vs not =): T-Value = 0.95  P-Value = 0.394  DF = 4
```

## 4.2 Analysis

For the first t-test the t-value was found to be .95. The corresponding p-value is .394. Since the p-value is .394 and is larger than the alpha of 0.05, the research does not support the hypothesis that the test cell particle count average is not equal to the ambient count. In order to verify these results, the t-test was applied to two additional random samples. For each instance, the statistical results were the same. The p-value was larger than the alpha in each case, supporting the earlier conclusion. Table 2 illustrates the resulting values from the additional t-tests.

Table 2. Results of Additional T-tests

| | T-value | P-value | df |
|---|---|---|---|
| **t-test 1** | 0.95 | .394 | 4 |
| **t-test 2** | -1.19 | .275 | 7 |
| **t-test 3** | -1.24 | .253 | 7 |

## 4.3 Summary

Data gathered in this study was sorted into two samples; the test cell samples and the ambient airport samples. To condition the data against outside influence, a subset of stable particle count values was generated from the samples. These subsets consisted of twenty individual data sets for each sample location. Five of these subset samples were then subjected to a two sample t-test. The first samples did not support the hypothesis that test cell particle count is not equal to the airport ambient count. In order to confirm this observation, the process was repeated two times with different random sample sets. These additional tests confirmed the conclusions of the first analysis.

# SECTION 5. CONCLUSIONS AND RECOMMENDATIONS

This section draws conclusions from the data that was gathered and analyzed in Section 4. Following the conclusions, recommendations for further operational considerations and future research are discussed.

## 5.1 Conclusions

After the first round of t-tests, the comparison of means showed that there is no statistically significant difference between ambient particle count of the airport property and the particulate count in the F109 test cell. The findings of this research led to the conclusion that the ambient nanoparticle count inherent to the F109 test cell is overall not higher than the nanoparticle count observed on the airport property. Analysis indicates possible lurking variables could exist, altering the results of this research, however these are not readily identifiable at this time. It should be noted that aircraft ground traffic frequently create increased levels in the samples. Figures 16 and 17 show examples of transient particle spikes created by taxiing aircraft subjecting the sampling station to increased particle concentrations above the normal line.

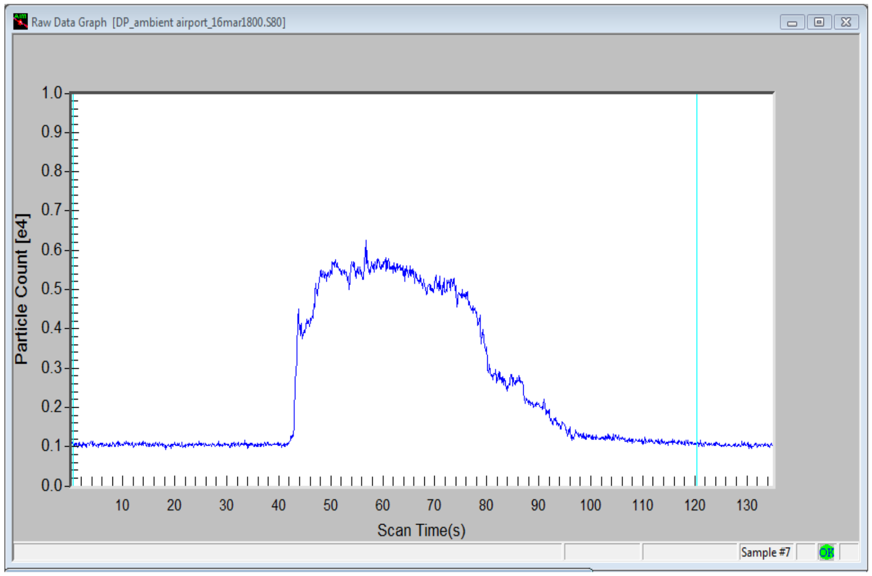



Figure 16. General Aviation Aircraft Transient

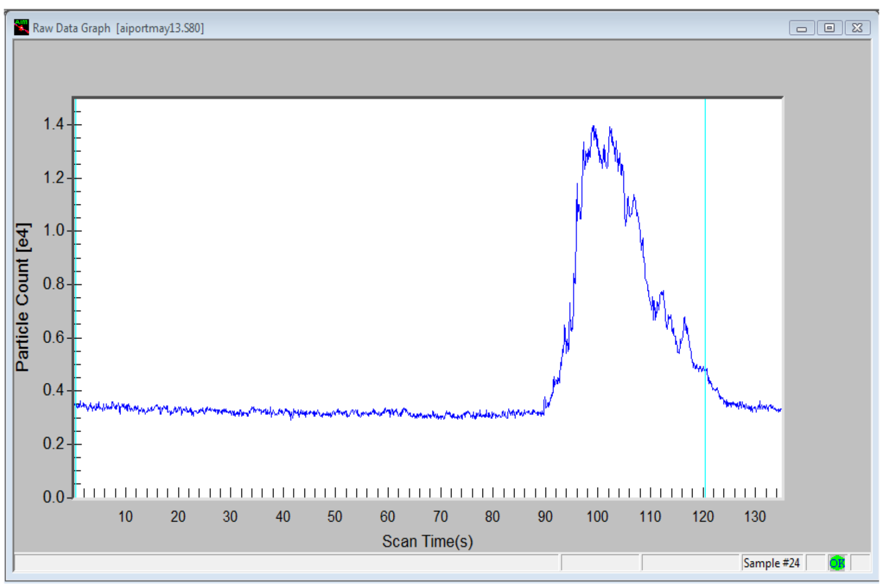



Figure 17. Particle Sampling Transient

In these figures, a clear spike in particle count was observed. A total of thirteen transients were observed during the airport sampling sessions. For different concentration spikes observed, the particle increase and duration of the spike varies directly with the aircraft type that passes the sampling station. For example, a turbine engine powered aircraft will increase the particle count and duration of transient observation more than a smaller piston engine aircraft does. Figure 18 is a composite image that illustrates this comparison in sampling corresponding to these instances.

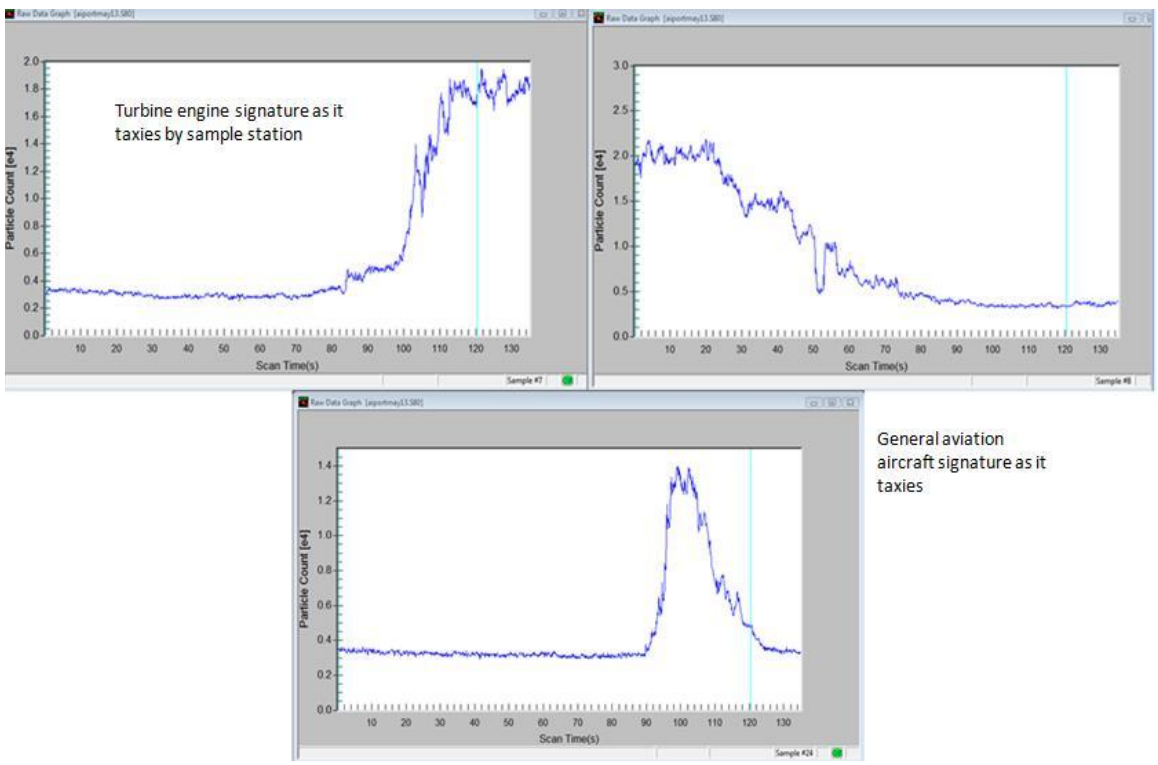



Figure 18. Transient Sample Comparison

## 5.2 <u>Recommendations</u>

Based on the conclusions gathered in this research, a variety of recommendations have been developed. There are a several factors that lead to the creation of PM emissions; however few of these are under the control of the airport. The Aviation Technology Department as well as the National Test Facility for Aerospace Fuels and Propulsion has the capability and resources to incorporate its assets to implement a real-time particulate monitoring system. This system can utilize the TSI Model 3776 Ultrafine Condensation Particle Counter to remotely sample the air quality inside the F109 test cell. This data can be linked to a monitor in the F109 test cell control room. With this system in place, personnel can be informed at all times of the current PM conditions inside the test cell and take appropriate protective action. Although personnel are not allowed into the test cell during engine operation, the conditions immediately afterward contain an extremely elevated particle count. Personnel should be encouraged to wear respirators or dust masks in these increased particle environments; particularly individuals with pre-existing conditions such as asthma. Respirators are a part of an equipment package that Aeronautical Engineering Technology students are required to possess. Dust masks are already in use in several lab settings such as the advanced composites courses due to the fiberglass particulate created over the course of the curriculum. Additionally, it is common for facilities that operate stationary sources install particle traps. A particle trap could be installed in the duct that channels the engine exhaust from the F109 engine test cell. This could drastically reduce the residual emissions in the test cell.

## 5.3 Future Research

Since the F109 engine used in the test cell never went into production, it is not characterized in the ICAO Engine Databank, the emissions data on this engine type is lacking. The emission profile for this engine needs to be generated in order to better understand the PM it generates. PM mass, distribution, and composition are all factors that could be addressed in a follow-on study. In addition to the PM research that is conducted, gaseous emission data also needs to be gathered.

EPA standards for PM2.5 are character in mass/$m^3$. As this research only quantified EIn, it is not possible to compare the results to EPA standards. Future studies should research mass measurements.

This research only sampled ambient particle counts in one location on the airport property. Future studies could be performed using a variety of different sites. These studies could yield different results. In addition, expert opinions could be gathered on locations on the airport property to sample. Field tests with the CPC equipment should be conducted to gain better understanding of the AIM software and CPC operation.

## 5.4 Summary

The addition of new equipment to the Aviation Technology Department has led to an increase in the capability to monitor exhaust emissions. As a result of this study, the knowledge of PM conditions inside the F109 test cell and the conditions out on the ramp of Purdue University Airport has been improved. Future monitoring of the PM conditions in locations at the Purdue University Airport may lead to improved understanding of environmental and health impacts of operating a test cell.

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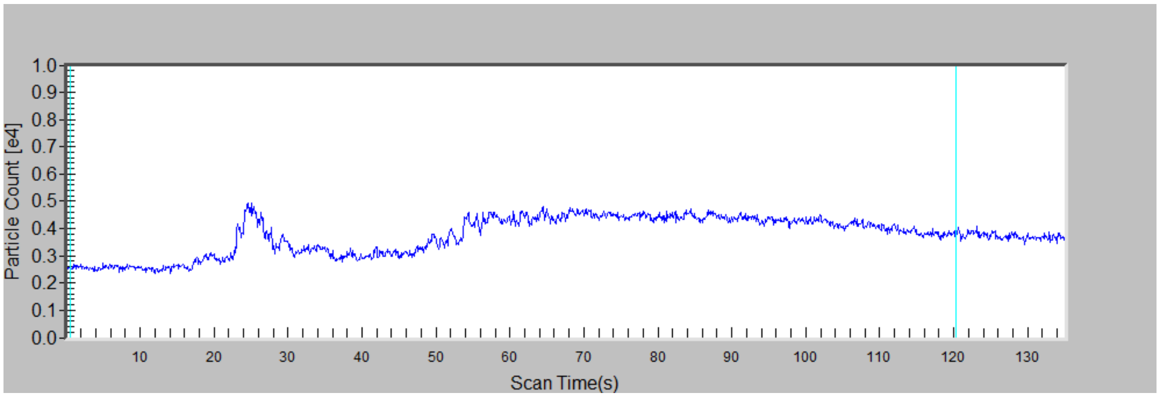
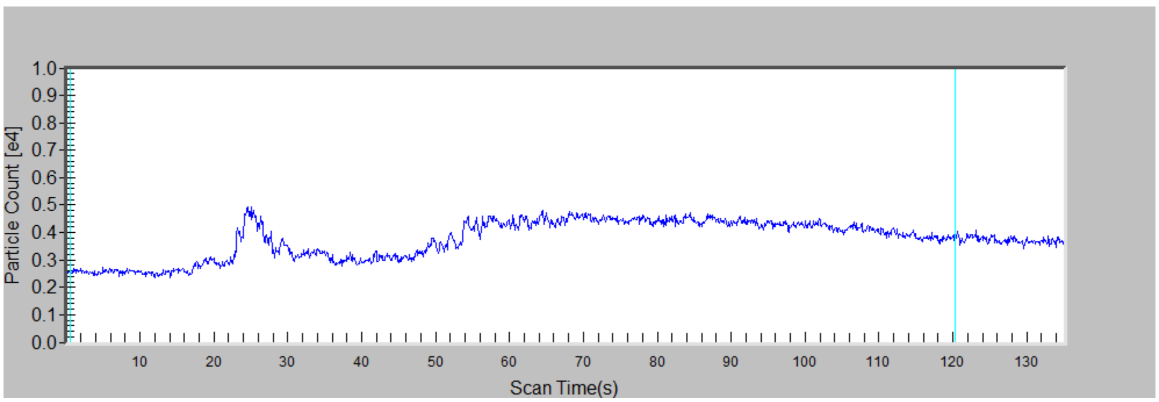
Appendix A. Representative Sample of AIM Real Time Raw Particle Count Graph

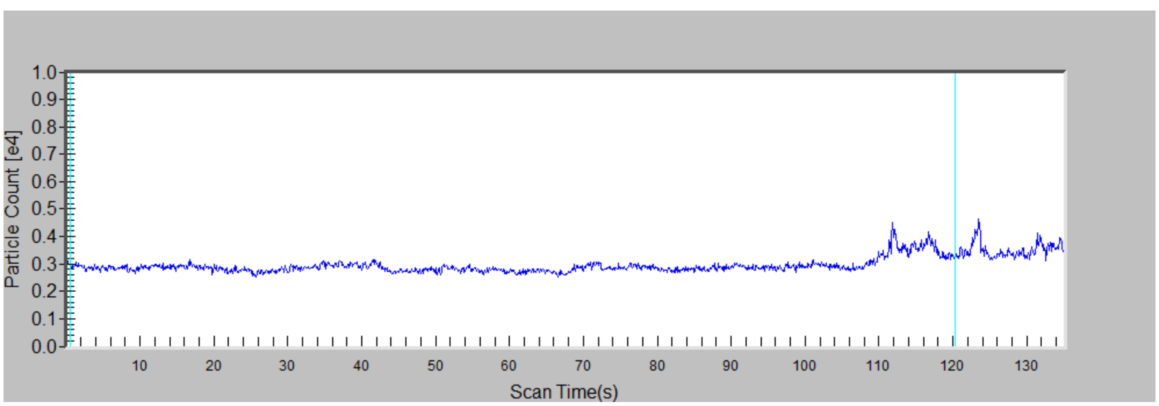
(Test Cell Sample Session 1)



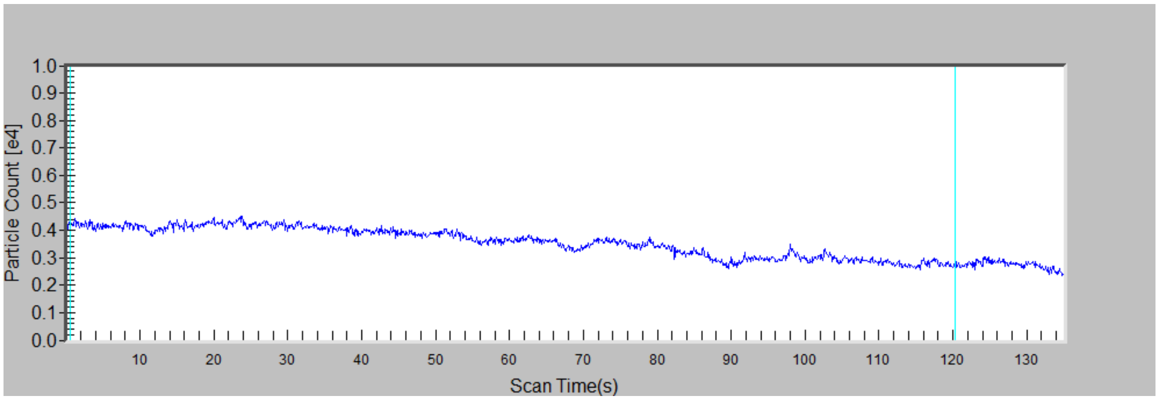

Sample 1



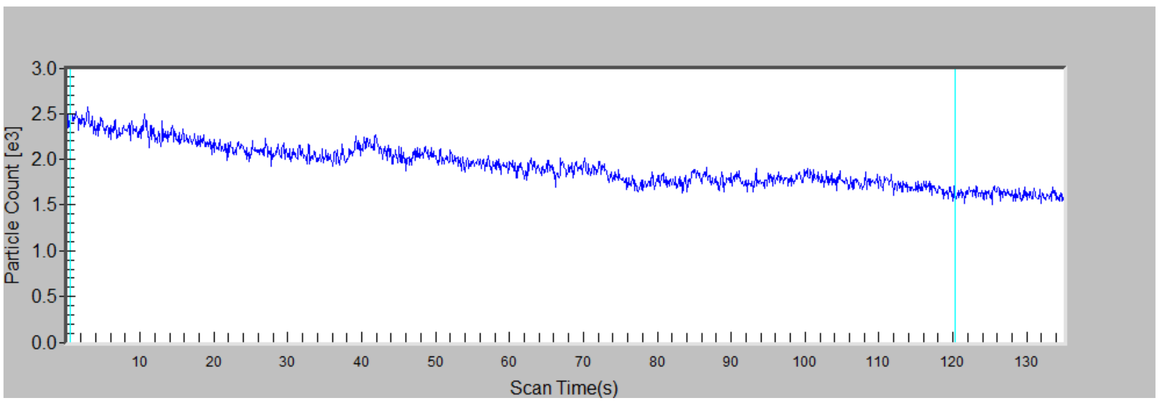

Sample 2



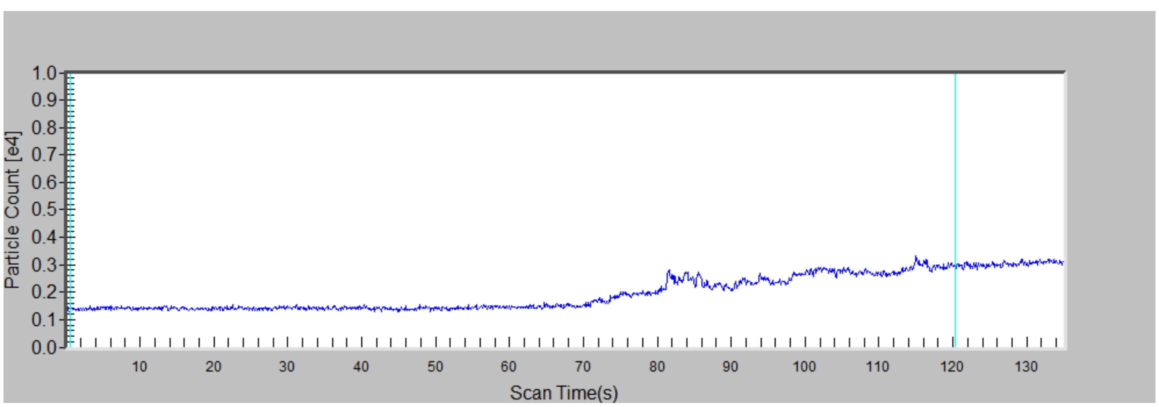

Sample 3



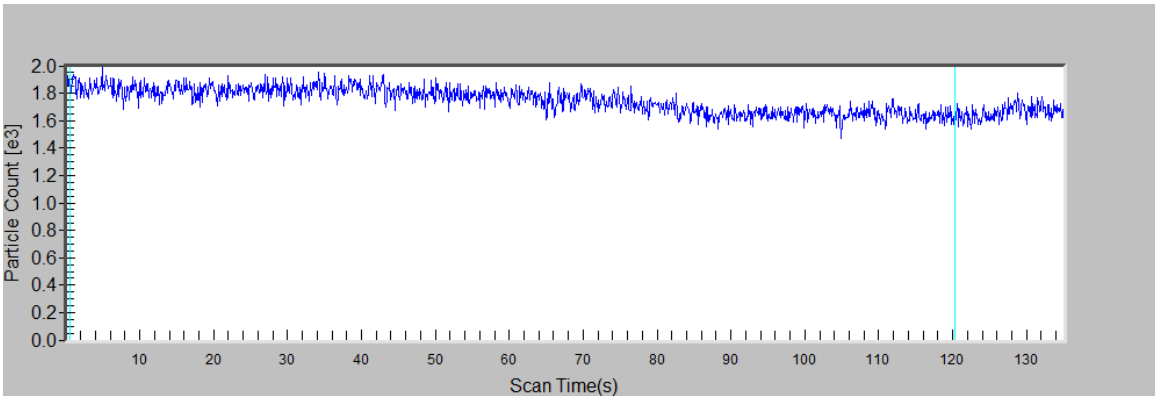

Sample 4



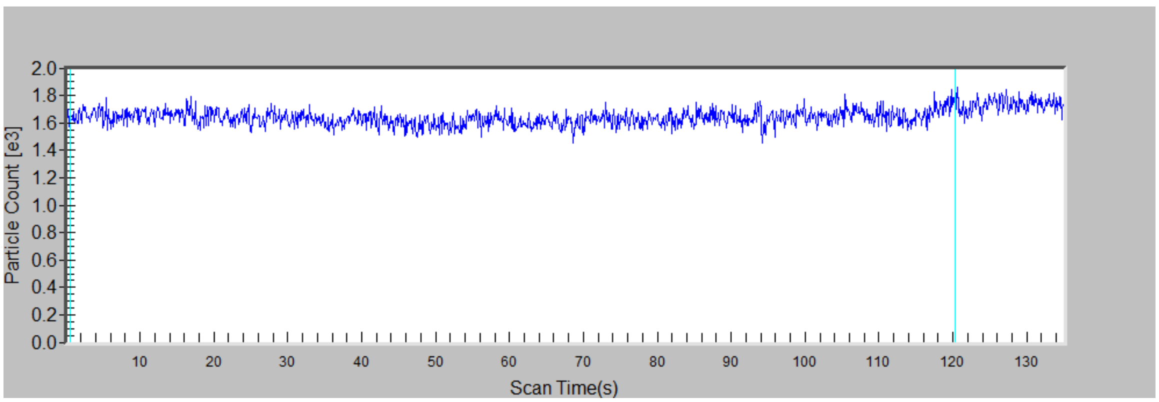

Sample 5



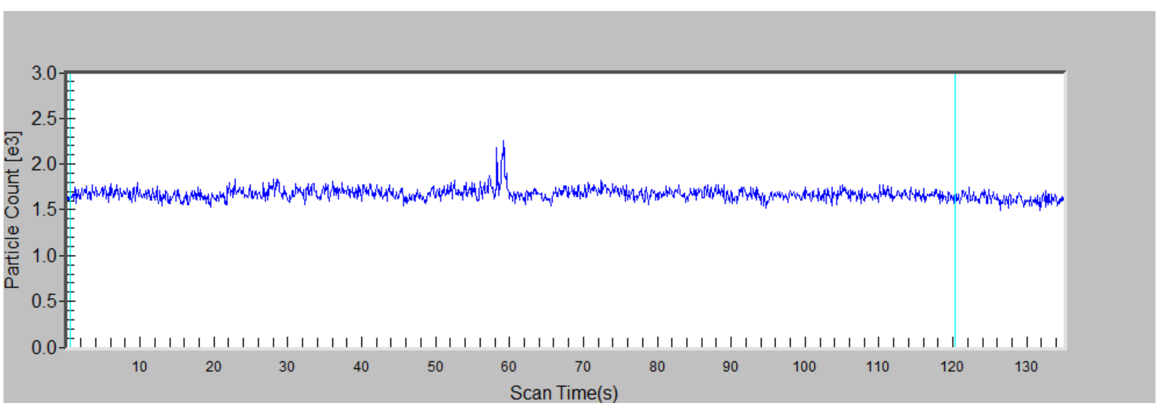

Sample 6



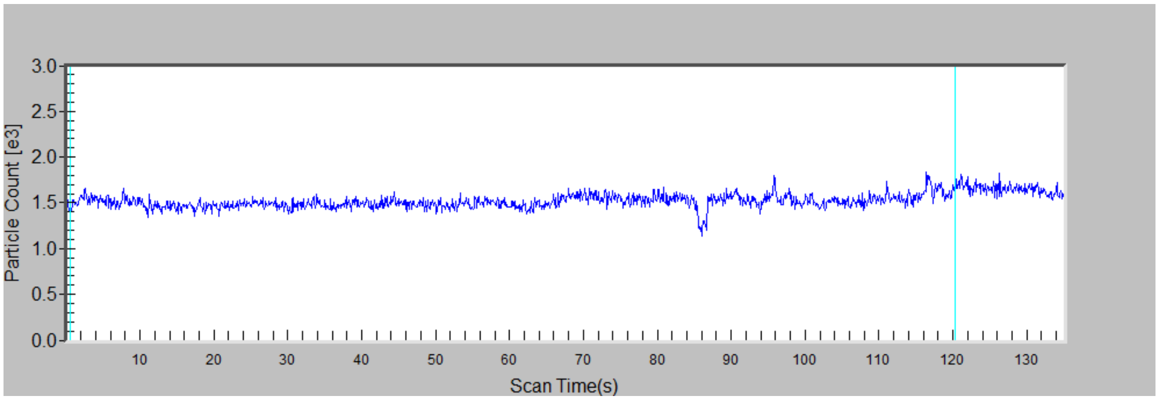

Sample 7



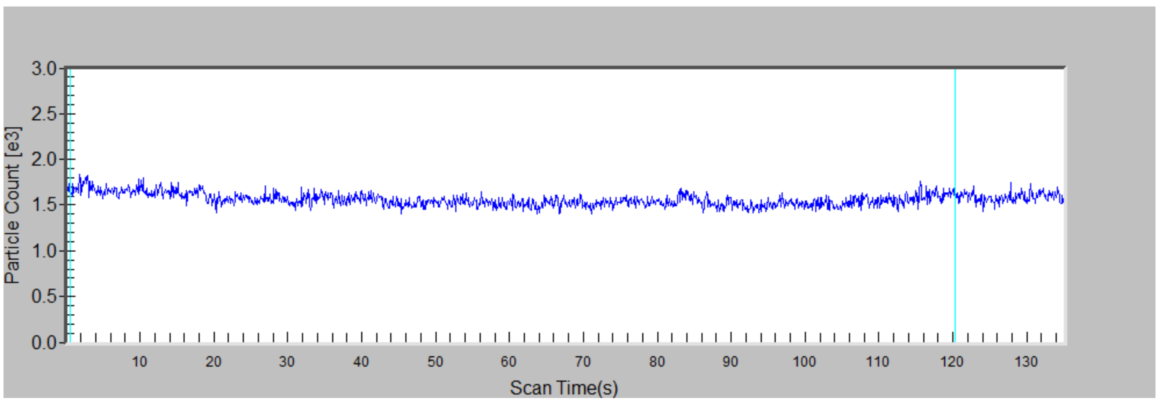

Sample 8



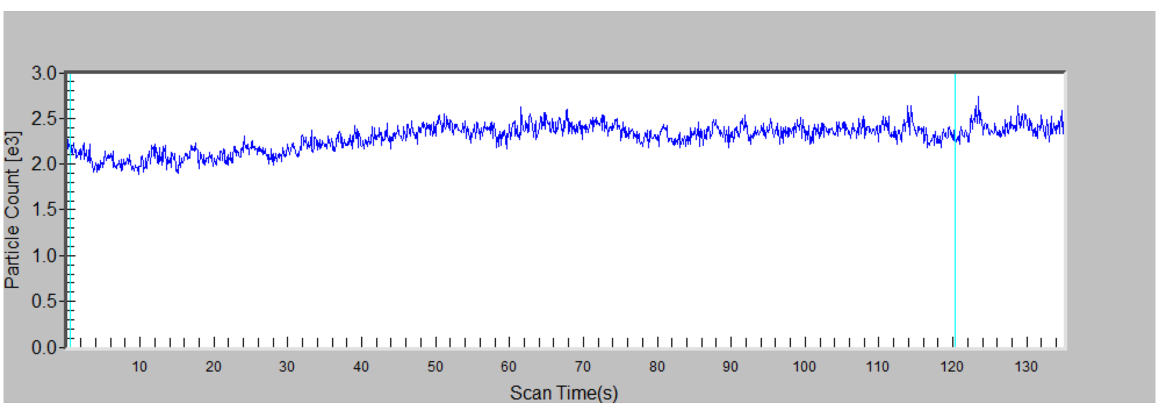

Sample 9



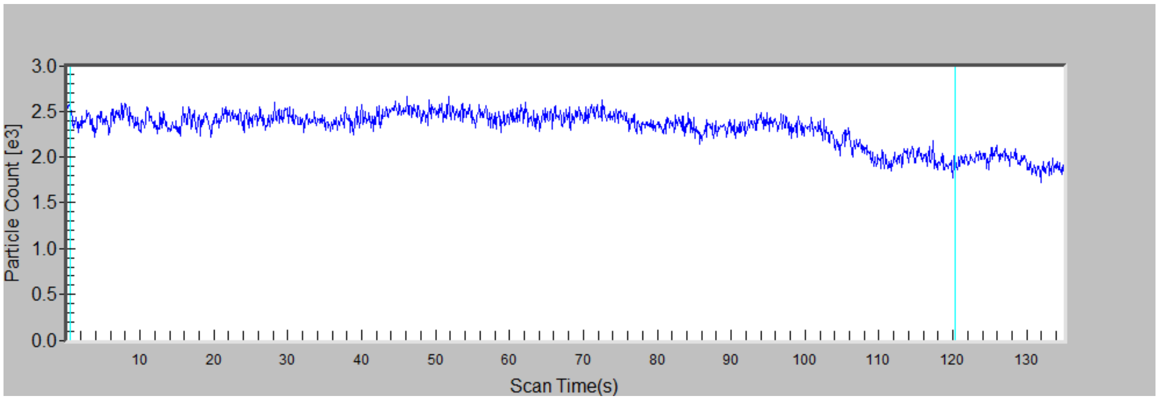

Sample 10



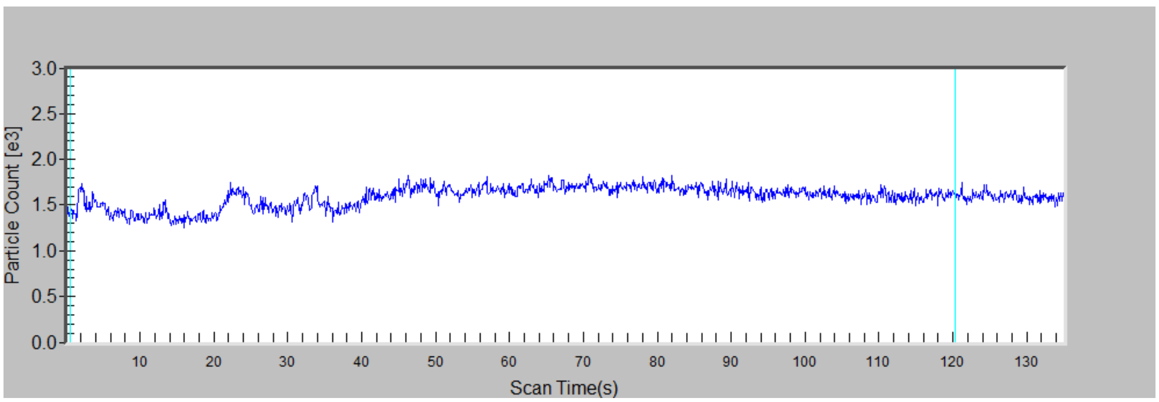

Sample 11



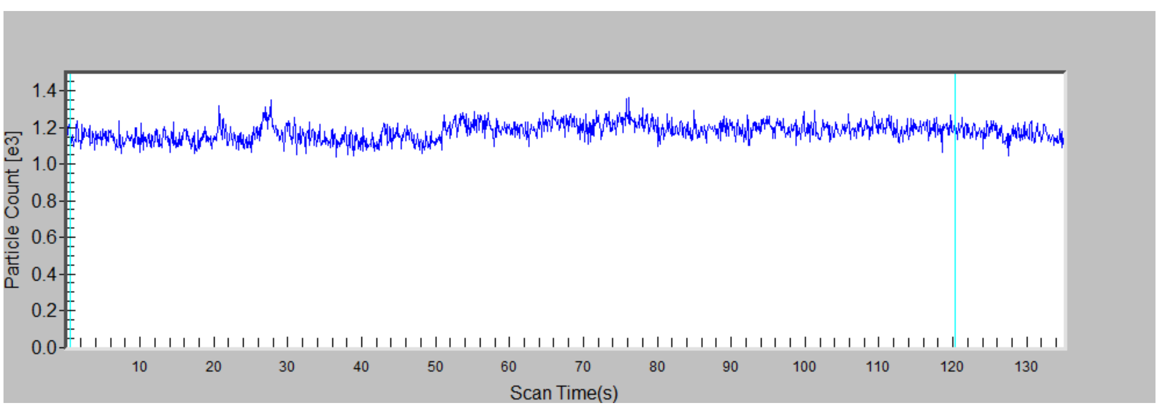

Sample 12



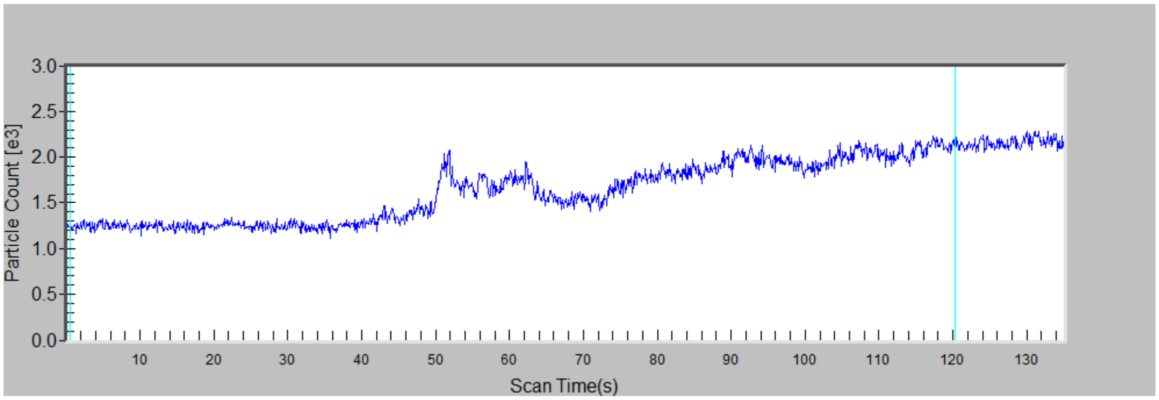

Sample 13



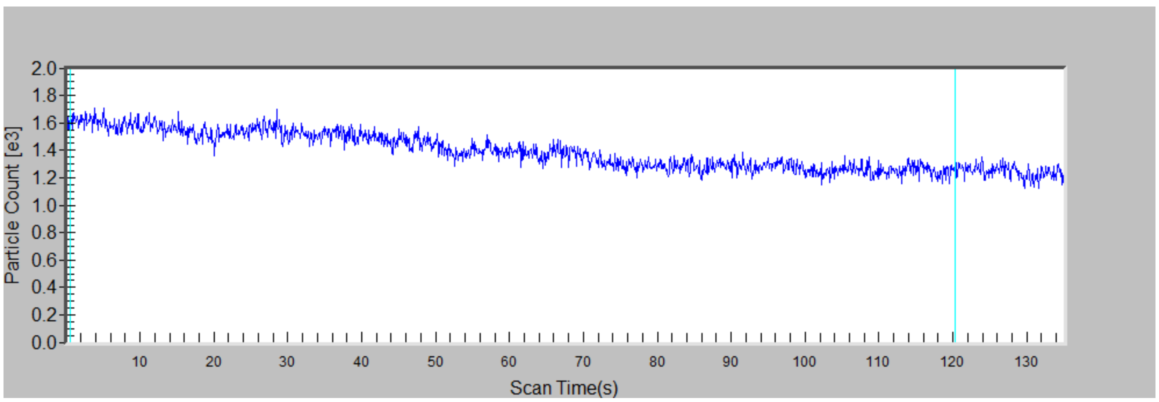

Sample 14



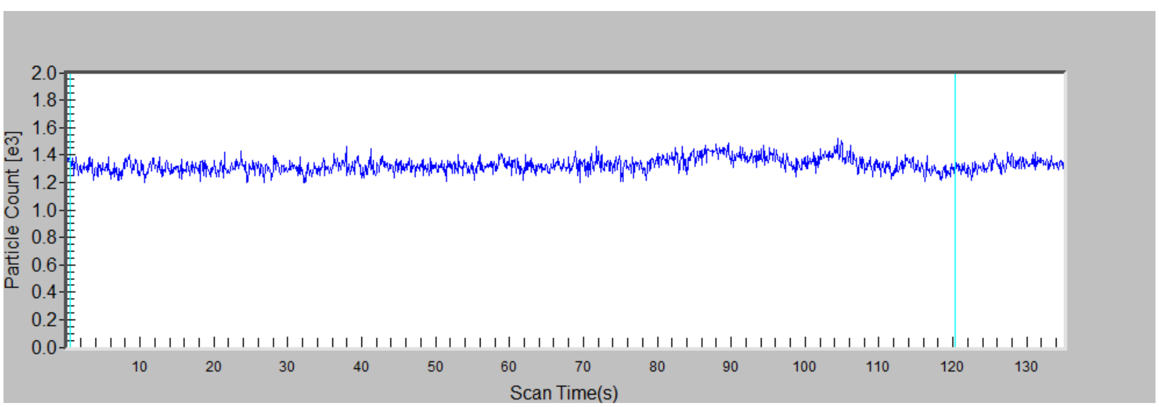

Sample 15



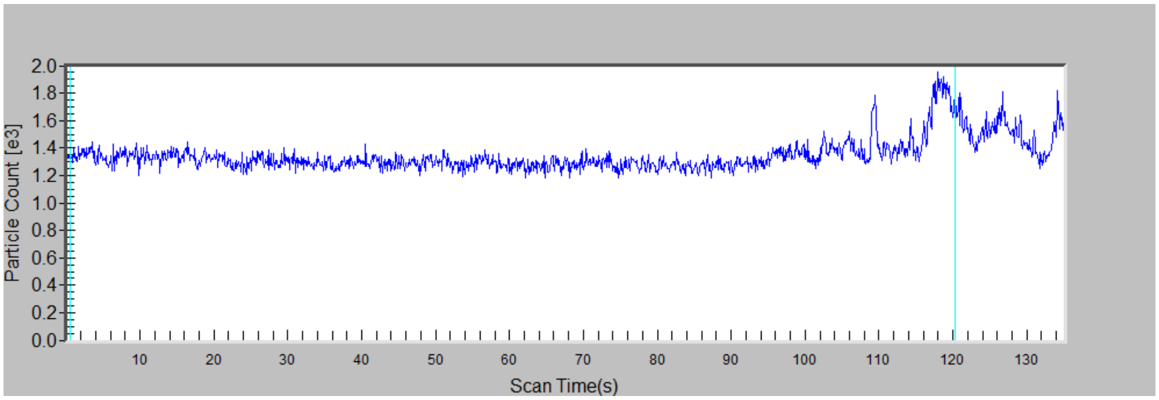

Sample 16



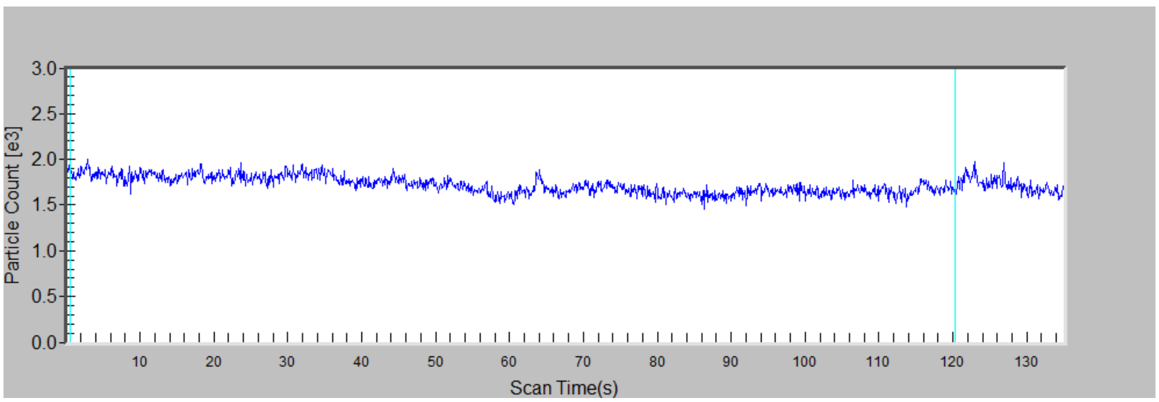

Sample 17



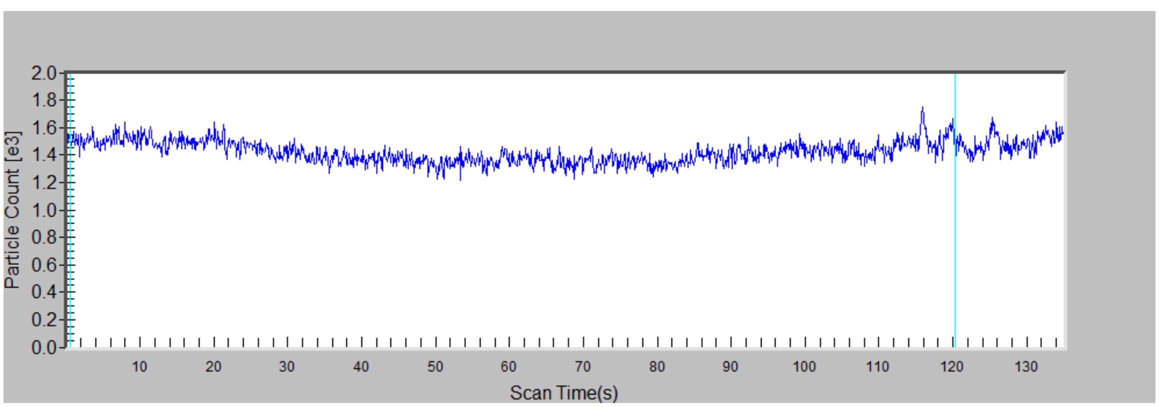

Sample 18



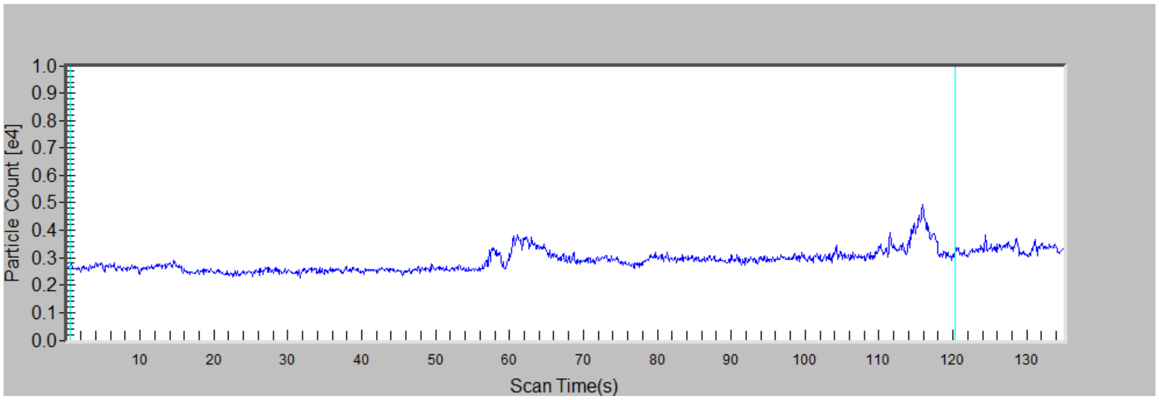

Sample 19



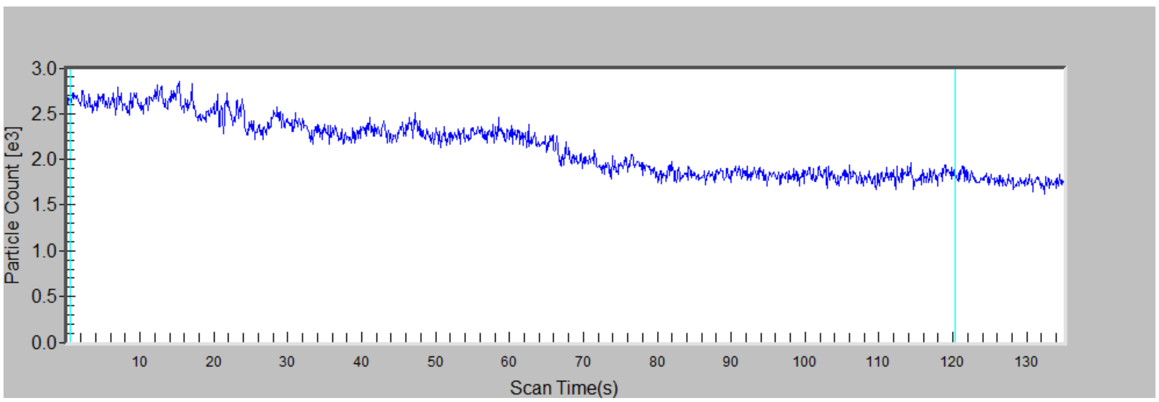

Sample 20



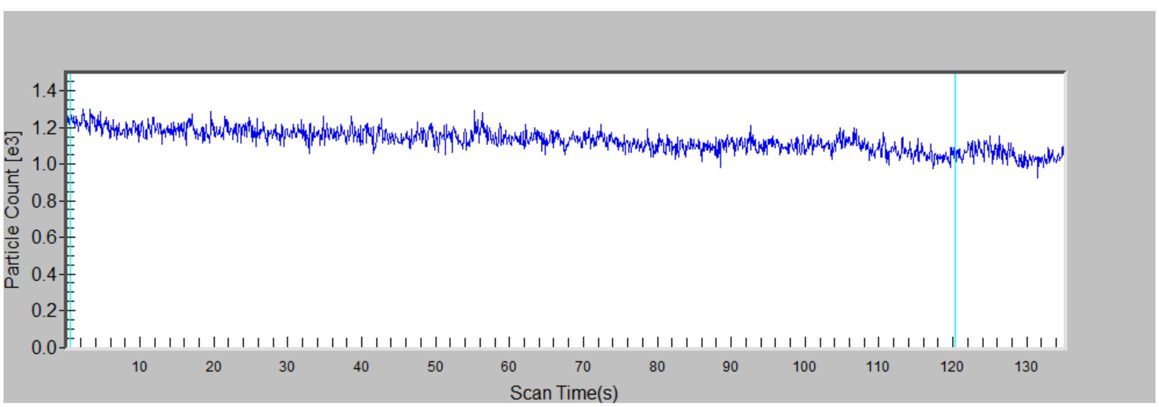

Sample 21



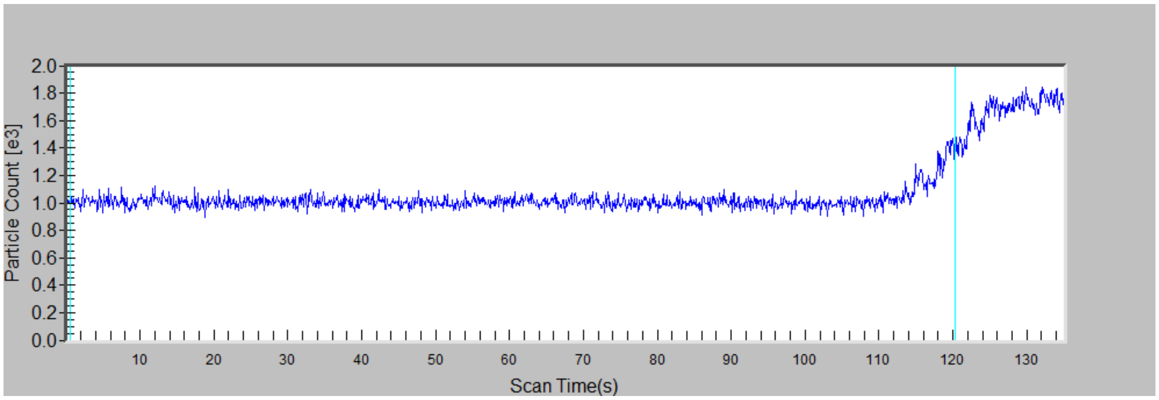

Sample 22




Sample 23



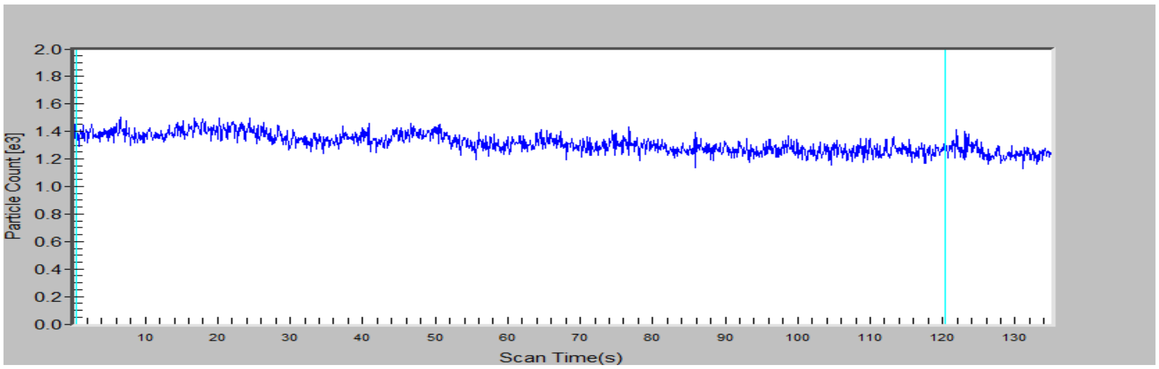

Sample 24


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Particle Count [e3]
10
20
30
40
50
60
70
80
90
100
110
120
130
Scan Time(s)

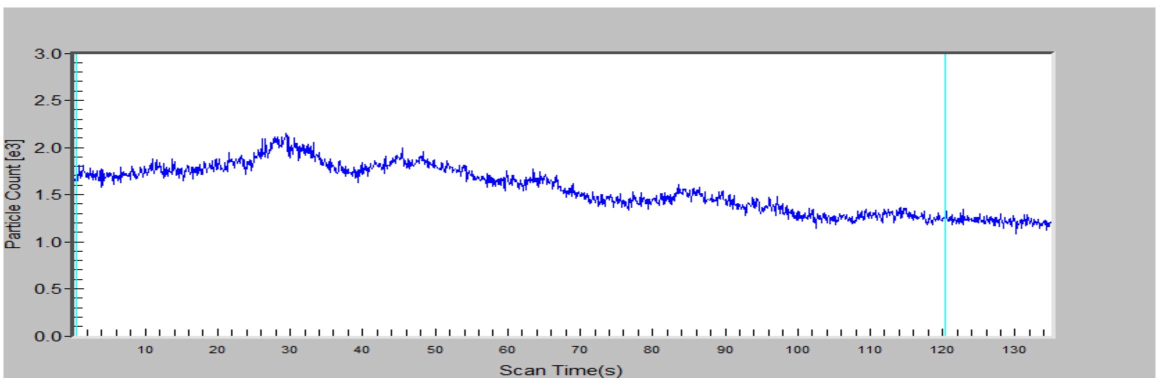
Sample 25

Appendix B. Representative Sample of AIM Real Time Raw Particle Count Graph

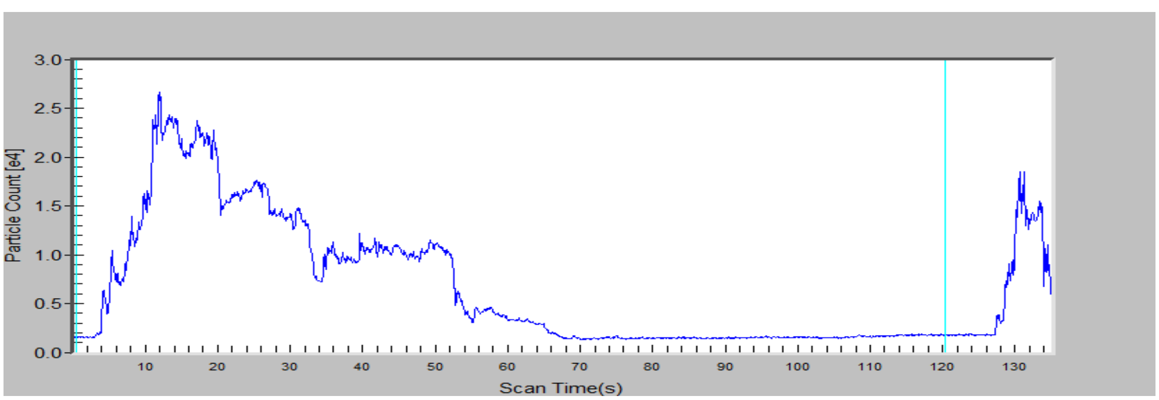
(Ambient Airport Sample Session 2)



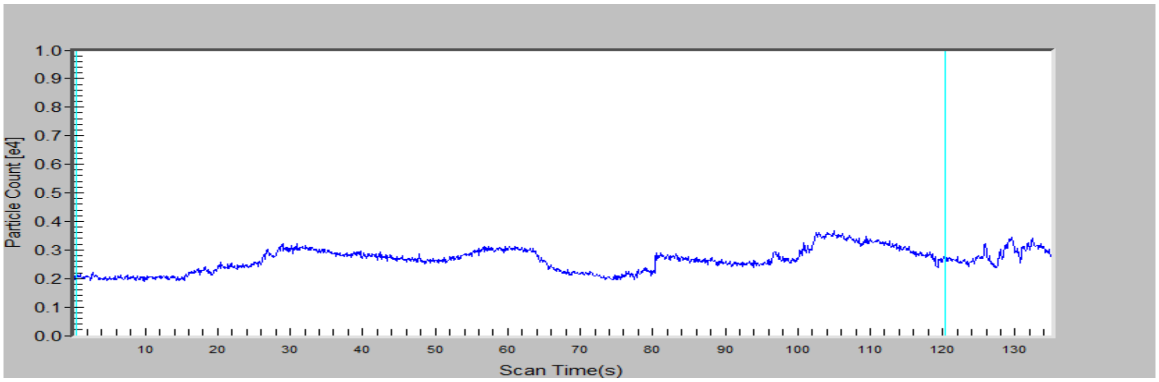

Sample 1



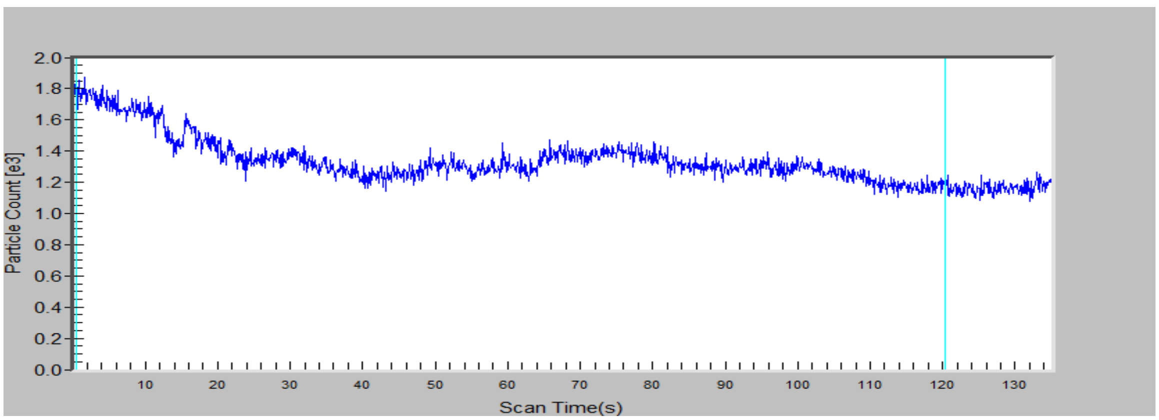

Sample 2



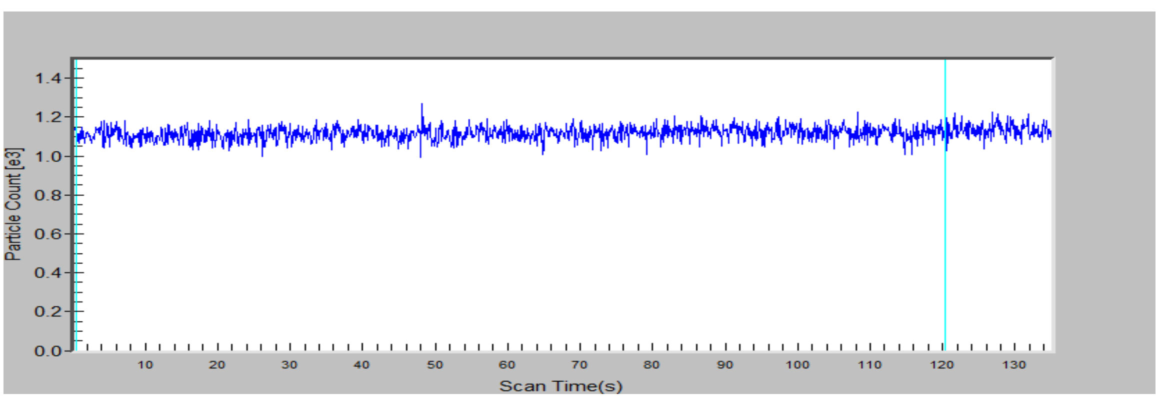

Sample 3



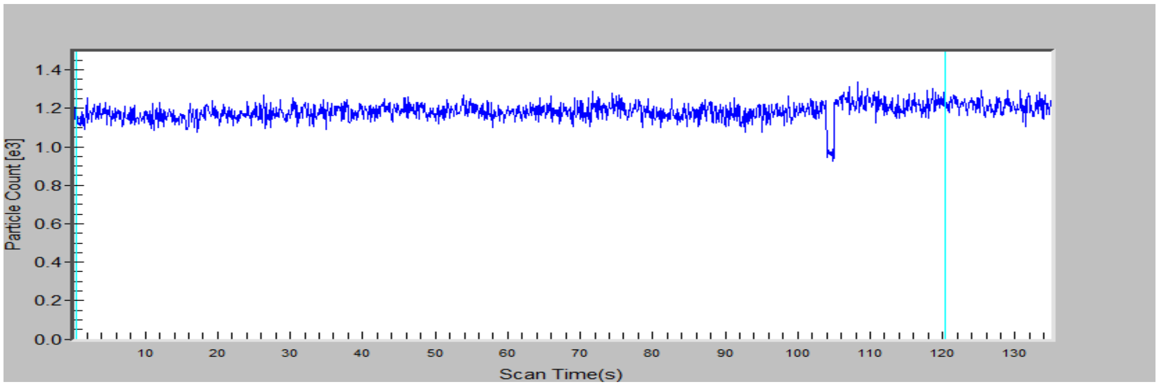

Sample 4



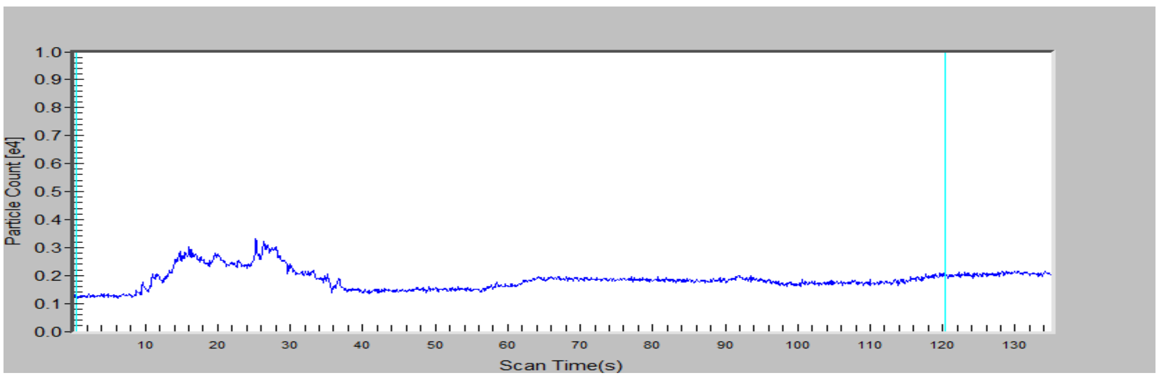

Sample 5



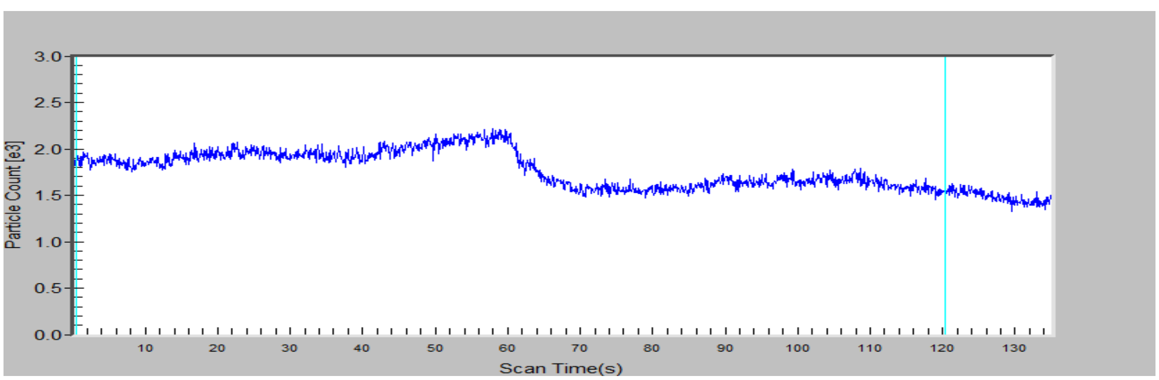

Sample 6



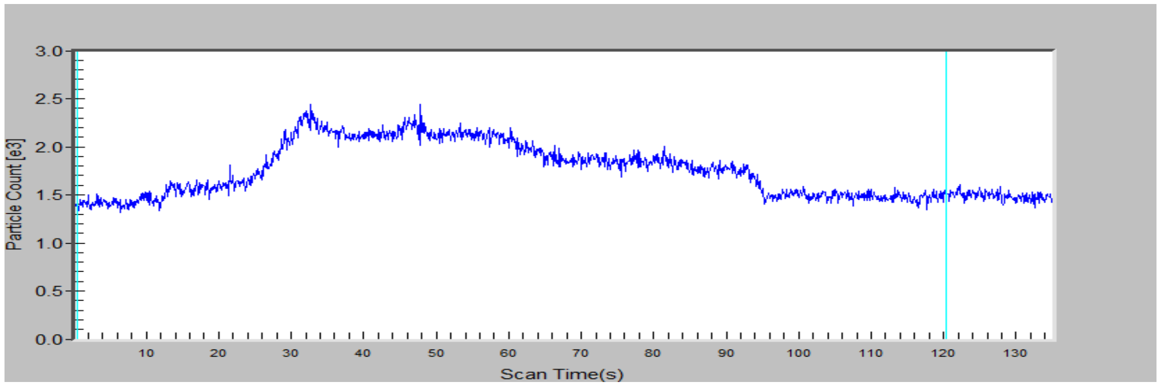

Sample 7



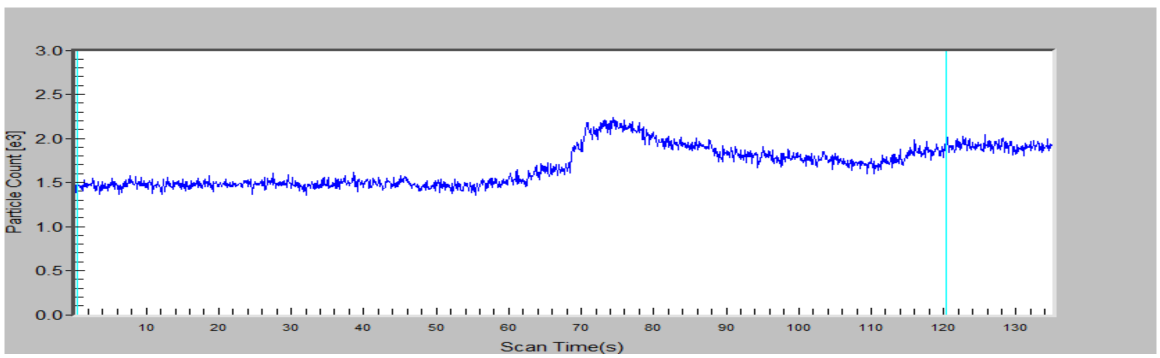

Sample 8



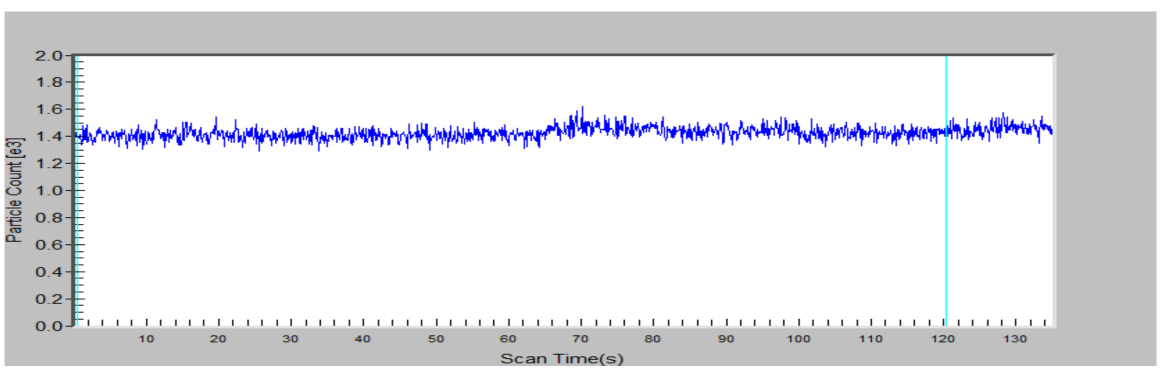

Sample 9



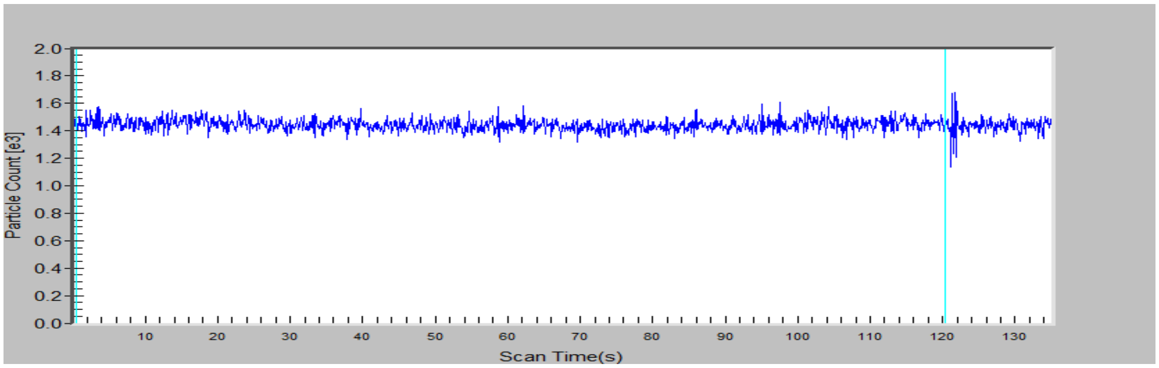

Sample 10



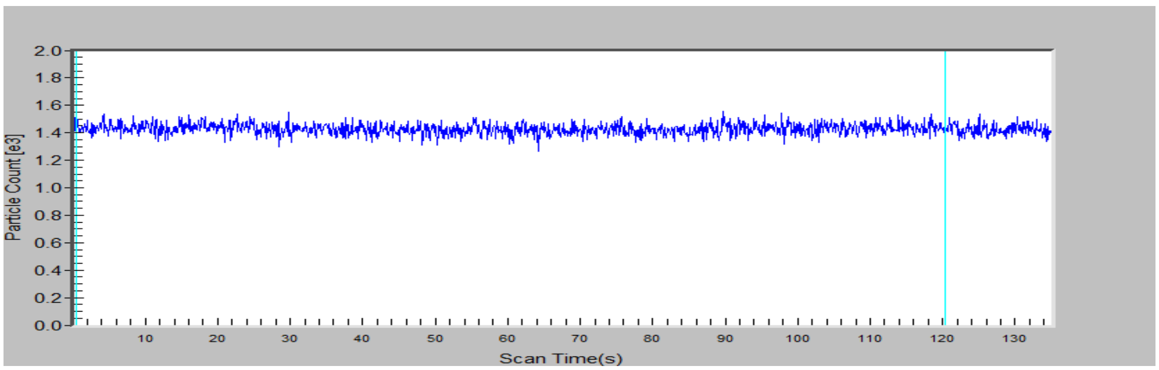

Sample 11



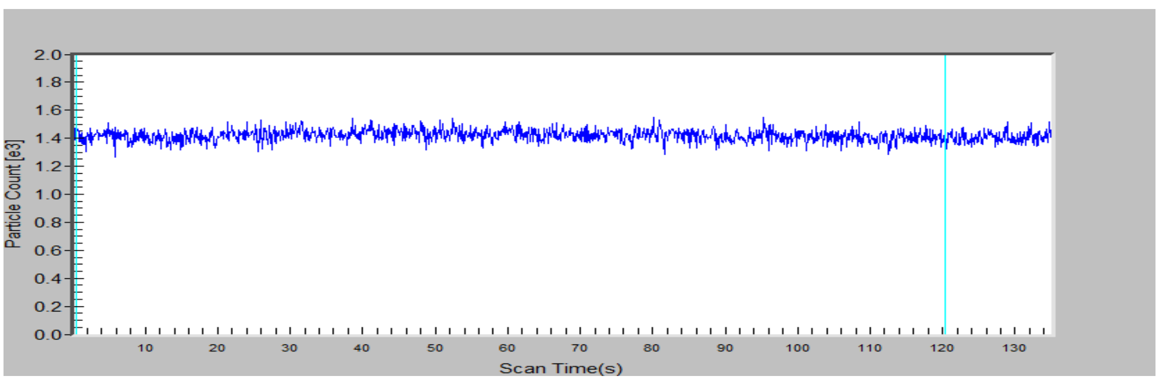

Sample 12



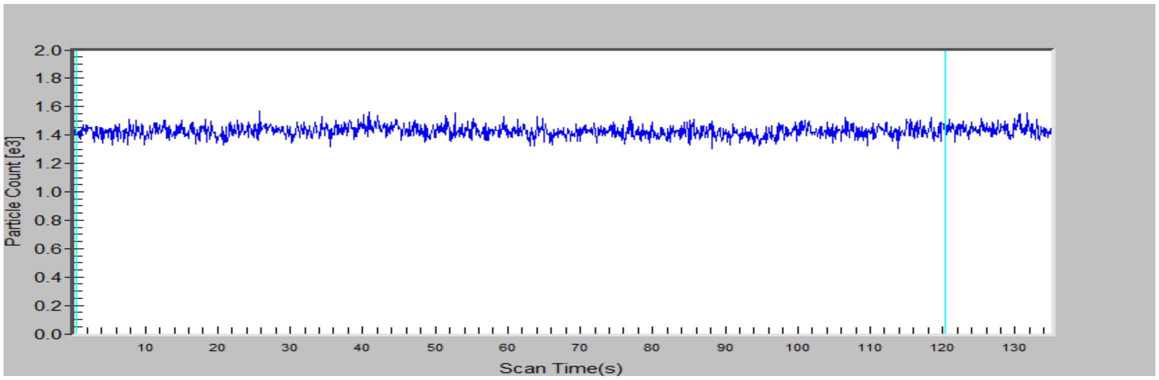

Sample 13



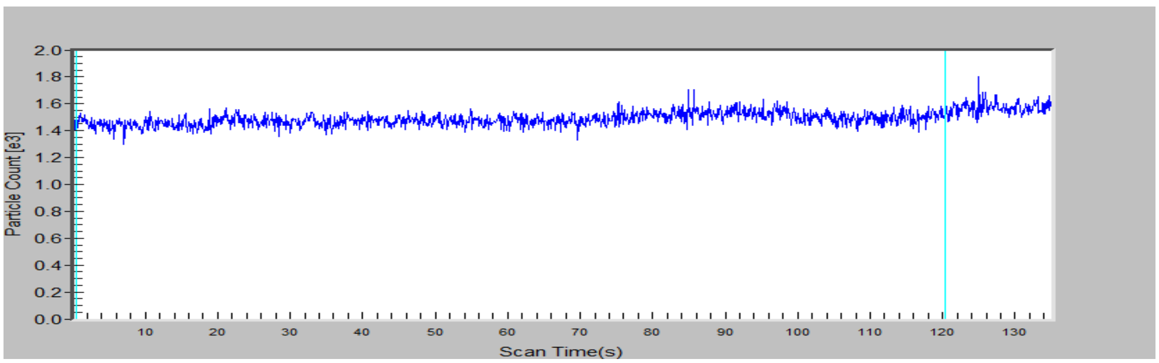

Sample 14



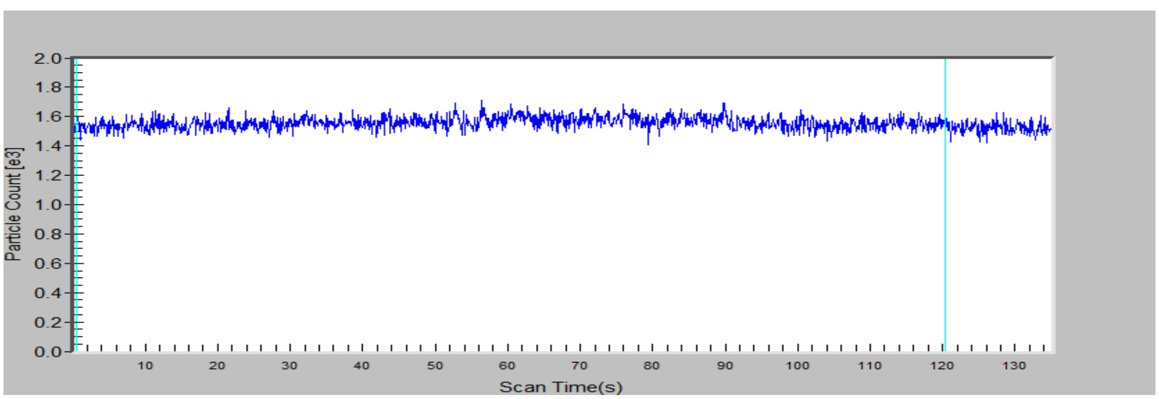

Sample 15



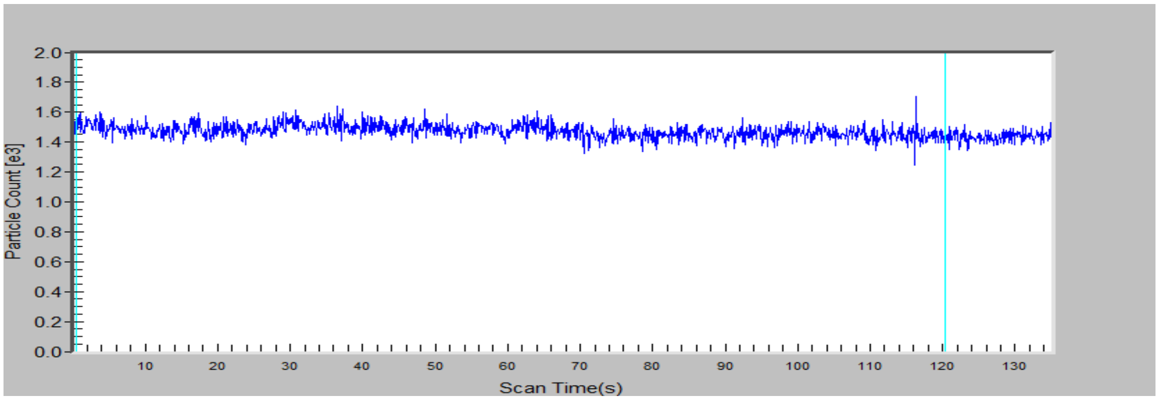

Sample 16



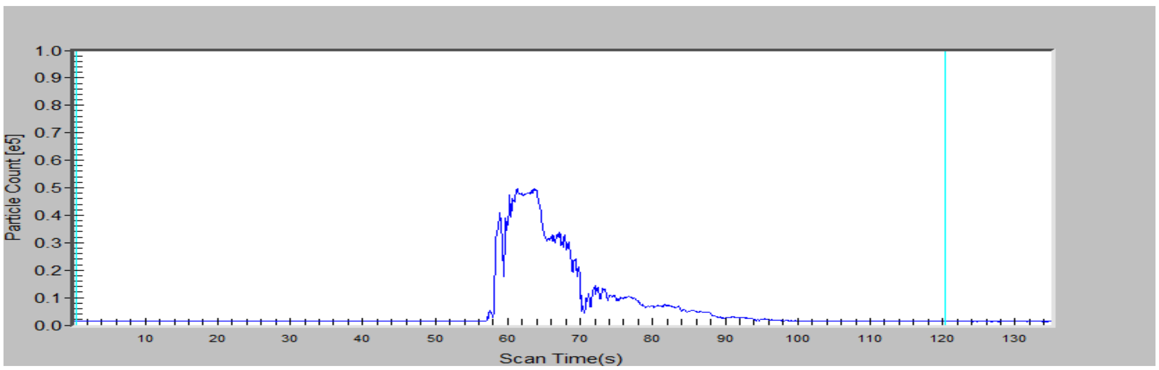

Sample 17



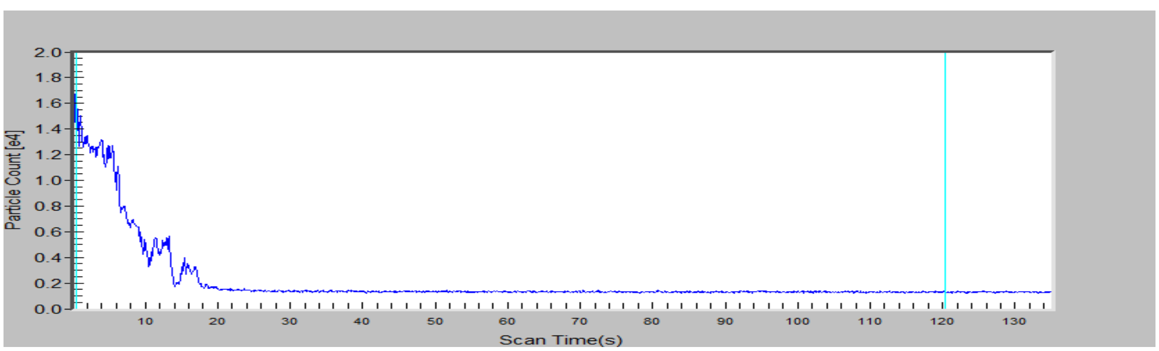

Sample 18



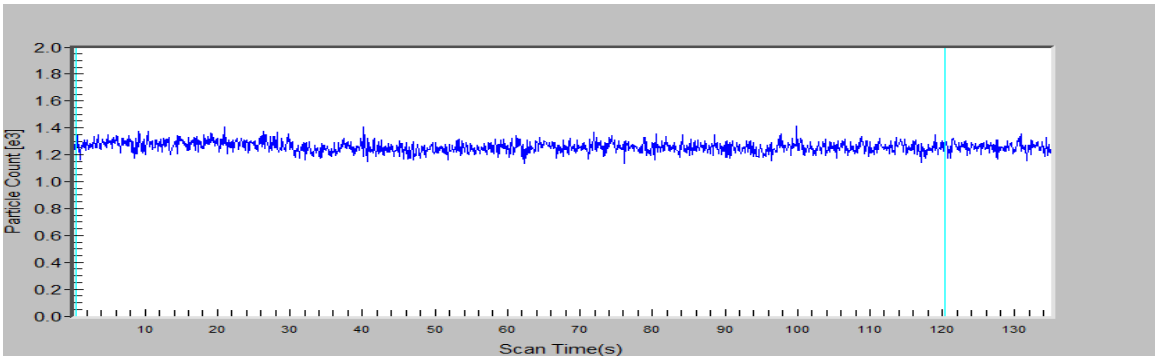

Sample 19



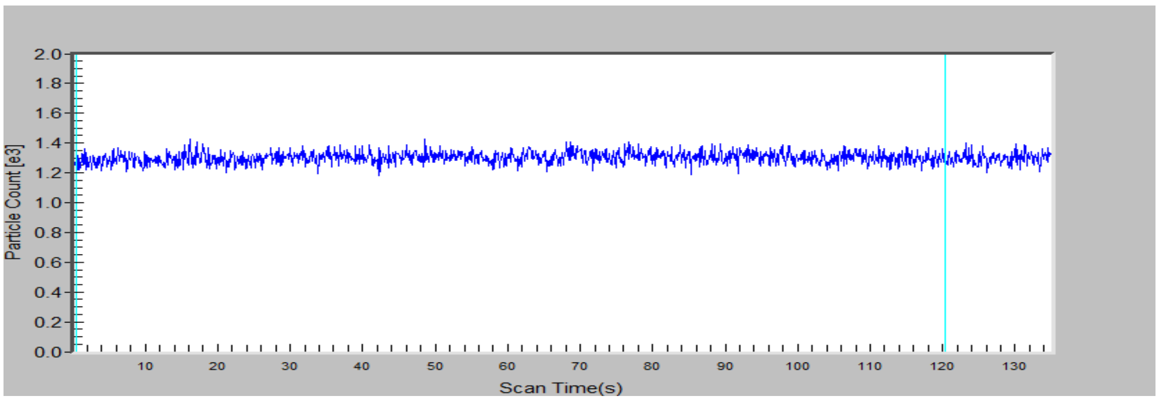

Sample 20



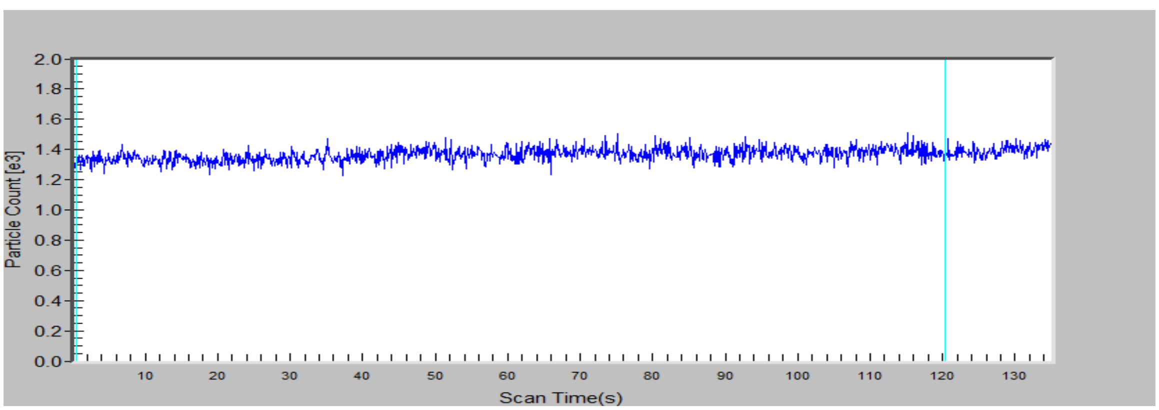

Sample 21



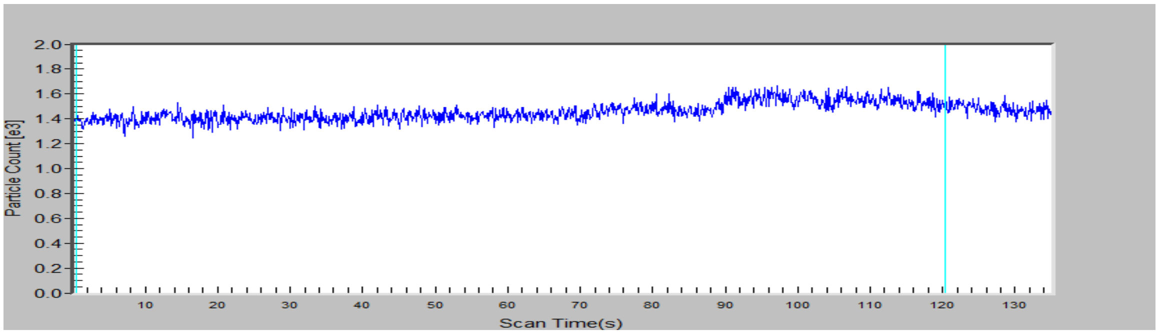

Sample 22




Sample 23




Sample 24


Particle Count [e3]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10
20
30
40
50
60
70
80
90
100
110
120
130
Scan Time(s)

Sample 25

Appendix C. Representative Sample of AIM Particle Count Data (Test Cell Sample Session 1)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 - 10 | 1058 | 1007 | 1006 | 1012 | 1000 | 940 | 1045 | 1000 | 1019 | 1028 |
| 11 - 20 | 1010 | 959 | 1029 | 1003 | 1015 | 1038 | 996 | 1000 | 934 | 945 |
| 21 - 30 | 1031 | 982 | 1096 | 971 | 995 | 1006 | 1059 | 1039 | 1027 | 1042 |
| 31 - 40 | 1022 | 1000 | 980 | 1009 | 1004 | 1045 | 1013 | 1010 | 1000 | 1025 |
| 41 - 50 | 1008 | 937 | 1014 | 956 | 1101 | 971 | 1043 | 1015 | 989 | 932 |
| 51 - 60 | 1063 | 979 | 990 | 1049 | 1031 | 1000 | 1107 | 972 | 982 | 1062 |
| 61 - 70 | 1046 | 1014 | 951 | 983 | 1041 | 1049 | 1047 | 1014 | 980 | 1008 |
| 71 - 80 | 969 | 968 | 1011 | 1006 | 1111 | 1011 | 1011 | 1034 | 927 | 1033 |
| 81 - 90 | 977 | 1040 | 986 | 954 | 960 | 934 | 983 | 942 | 965 | 1028 |
| 91 - 100 | 1012 | 1002 | 951 | 989 | 969 | 1018 | 1031 | 1040 | 1019 | 1032 |
| 101 - 110 | 1033 | 1065 | 1026 | 1019 | 996 | 1018 | 983 | 1006 | 1050 | 1008 |
| 111 - 120 | 952 | 1003 | 987 | 1040 | 979 | 980 | 1105 | 1024 | 1013 | 1119 |
| 121 - 130 | 1029 | 1039 | 1028 | 1036 | 1004 | 1033 | 1041 | 1001 | 984 | 1055 |
| 131 - 140 | 1085 | 1052 | 1046 | 1029 | 1013 | 1019 | 1002 | 994 | 1083 | 1019 |
| 141 - 150 | 988 | 1029 | 1010 | 953 | 981 | 1052 | 930 | 1015 | 994 | 962 |
| 151 - 160 | 1012 | 1047 | 946 | 1031 | 1000 | 1041 | 1018 | 1008 | 1023 | 1006 |
| 161 - 170 | 1003 | 1047 | 995 | 967 | 1013 | 974 | 971 | 952 | 983 | 1022 |
| 171 - 180 | 1009 | 960 | 994 | 1118 | 984 | 1008 | 940 | 1074 | 970 | 944 |
| 181 - 190 | 966 | 956 | 1029 | 967 | 1020 | 1012 | 1006 | 895 | 1002 | 979 |
| 191 - 200 | 1015 | 1048 | 971 | 999 | 997 | 1007 | 1011 | 1013 | 1047 | 1013 |
| 201 - 210 | 1023 | 962 | 1048 | 1004 | 967 | 1001 | 1090 | 1004 | 1026 | 976 |
| 211 - 220 | 950 | 972 | 998 | 1056 | 1024 | 992 | 1015 | 971 | 967 | 1098 |
| 221 - 230 | 1001 | 1028 | 962 | 1000 | 997 | 1025 | 1031 | 951 | 979 | 1009 |
| 231 - 240 | 967 | 984 | 944 | 948 | 1056 | 964 | 975 | 959 | 968 | 991 |
| 241 - 250 | 1039 | 1027 | 970 | 1049 | 1002 | 1030 | 1050 | 982 | 1014 | 989 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 251 - 260 | 973 | 1048 | 987 | 978 | 1024 | 942 | 1026 | 960 | 1024 | 1021 |
| 261 - 270 | 1047 | 990 | 992 | 1040 | 1001 | 1058 | 1027 | 947 | 1014 | 1035 |
| 271 - 280 | 1032 | 981 | 1022 | 1021 | 985 | 1009 | 984 | 1003 | 1015 | 1050 |
| 281 - 290 | 983 | 1000 | 1010 | 1005 | 1043 | 1040 | 1011 | 1009 | 1013 | 999 |
| 291 - 300 | 961 | 1035 | 1008 | 973 | 1019 | 979 | 988 | 1023 | 1037 | 972 |
| 301 - 310 | 1023 | 988 | 1000 | 1005 | 1008 | 1005 | 1036 | 966 | 995 | 1044 |
| 311 - 320 | 956 | 964 | 975 | 933 | 1023 | 1053 | 1018 | 990 | 1014 | 1061 |
| 321 - 330 | 974 | 1004 | 1055 | 1072 | 1054 | 919 | 1003 | 1044 | 1070 | 1015 |
| 331 - 340 | 1097 | 1033 | 1020 | 979 | 1009 | 1013 | 968 | 1022 | 974 | 1008 |
| 341 - 350 | 1076 | 963 | 1037 | 1001 | 979 | 1042 | 1011 | 1080 | 1020 | 988 |
| 351 - 360 | 992 | 982 | 991 | 1006 | 982 | 1021 | 1010 | 990 | 1018 | 1003 |
| 361 - 370 | 960 | 1005 | 1039 | 1001 | 1032 | 1018 | 1055 | 979 | 974 | 1000 |
| 371 - 380 | 983 | 1019 | 993 | 934 | 999 | 1065 | 940 | 1044 | 1021 | 1032 |
| 381 - 390 | 1009 | 1022 | 998 | 972 | 1046 | 973 | 1027 | 979 | 967 | 941 |
| 391 - 400 | 940 | 989 | 972 | 993 | 1054 | 961 | 963 | 1019 | 1031 | 1004 |
| 401 - 410 | 1043 | 1021 | 1017 | 1028 | 1019 | 1002 | 1064 | 1027 | 1059 | 985 |
| 411 - 420 | 993 | 986 | 1027 | 1018 | 1071 | 950 | 974 | 1016 | 980 | 1008 |
| 421 - 430 | 998 | 1032 | 1095 | 1010 | 1020 | 1006 | 1011 | 1041 | 1019 | 1005 |
| 431 - 440 | 1044 | 952 | 951 | 1026 | 1002 | 978 | 989 | 989 | 958 | 982 |
| 441 - 450 | 1012 | 1007 | 1032 | 994 | 997 | 1009 | 1006 | 999 | 990 | 1044 |
| 451 - 460 | 1003 | 942 | 1011 | 965 | 965 | 1002 | 987 | 1005 | 1009 | 1000 |
| 461 - 470 | 1035 | 1037 | 958 | 1006 | 940 | 977 | 954 | 1000 | 1036 | 1007 |
| 471 - 480 | 965 | 1040 | 987 | 1004 | 995 | 998 | 1086 | 977 | 975 | 1032 |
| 481 - 490 | 930 | 1027 | 1015 | 1010 | 1004 | 969 | 993 | 1037 | 1021 | 1002 |
| 491 - 500 | 1025 | 991 | 1003 | 949 | 987 | 1050 | 978 | 1002 | 975 | 989 |
| 501 - 510 | 965 | 1050 | 988 | 1015 | 984 | 996 | 977 | 995 | 993 | 961 |
| 511 - 520 | 1057 | 986 | 1046 | 996 | 975 | 1067 | 982 | 980 | 972 | 988 |
| 521 - 530 | 977 | 983 | 1024 | 948 | 970 | 995 | 1000 | 956 | 1027 | 1010 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 531 - 540 | 1002 | 947 | 981 | 975 | 1010 | 990 | 977 | 1024 | 964 | 1085 |
| 541 - 550 | 1003 | 964 | 1009 | 978 | 1014 | 988 | 973 | 985 | 1013 | 1007 |
| 551 - 560 | 1048 | 1013 | 1075 | 1007 | 995 | 982 | 1053 | 1040 | 998 | 1021 |
| 561 - 570 | 992 | 1022 | 1039 | 1002 | 1039 | 989 | 1018 | 1005 | 985 | 986 |
| 571 - 580 | 997 | 1018 | 971 | 960 | 1024 | 993 | 1000 | 1015 | 976 | 1047 |
| 581 - 590 | 977 | 1003 | 1003 | 1057 | 1000 | 970 | 1058 | 994 | 1013 | 1031 |
| 591 - 600 | 1013 | 940 | 1038 | 987 | 1009 | 978 | 1035 | 1014 | 995 | 1024 |
| 601 - 610 | 1043 | 1006 | 968 | 1026 | 962 | 1012 | 1078 | 1032 | 981 | 1015 |
| 611 - 620 | 997 | 985 | 1011 | 982 | 1025 | 1029 | 1055 | 979 | 1027 | 1015 |
| 621 - 630 | 1021 | 1027 | 1066 | 1034 | 1012 | 1031 | 998 | 1036 | 1069 | 994 |
| 631 - 640 | 1065 | 999 | 995 | 1003 | 997 | 983 | 1023 | 1019 | 984 | 955 |
| 641 - 650 | 991 | 990 | 981 | 988 | 1024 | 1025 | 1030 | 989 | 1038 | 996 |
| 651 - 660 | 1033 | 968 | 987 | 1008 | 997 | 1025 | 1037 | 1022 | 1028 | 1006 |
| 661 - 670 | 1038 | 1068 | 999 | 1040 | 955 | 1015 | 1007 | 989 | 972 | 971 |
| 671 - 680 | 962 | 1025 | 1025 | 999 | 926 | 1022 | 969 | 976 | 1035 | 1041 |
| 681 - 690 | 999 | 1002 | 1045 | 1072 | 984 | 986 | 1005 | 1053 | 1069 | 1042 |
| 691 - 700 | 1009 | 990 | 980 | 1008 | 988 | 993 | 1030 | 1001 | 997 | 1009 |
| 701 - 710 | 1031 | 1010 | 963 | 951 | 1032 | 1013 | 999 | 1056 | 957 | 1035 |
| 711 - 720 | 1041 | 1077 | 973 | 1005 | 1002 | 1020 | 1021 | 1070 | 1003 | 1025 |
| 721 - 730 | 1002 | 991 | 985 | 960 | 960 | 963 | 1003 | 971 | 925 | 1057 |
| 731 - 740 | 1025 | 971 | 1081 | 978 | 1059 | 965 | 978 | 947 | 936 | 1012 |
| 741 - 750 | 994 | 958 | 1021 | 963 | 1011 | 990 | 1076 | 1019 | 977 | 972 |
| 751 - 760 | 991 | 985 | 1001 | 1012 | 1060 | 998 | 1023 | 938 | 946 | 965 |
| 761 - 770 | 1023 | 987 | 998 | 957 | 1038 | 1020 | 995 | 971 | 970 | 1030 |
| 771 - 780 | 970 | 987 | 1033 | 936 | 964 | 1020 | 987 | 979 | 1021 | 985 |
| 781 - 790 | 999 | 1040 | 1025 | 1049 | 1040 | 997 | 996 | 979 | 1029 | 949 |
| 791 - 800 | 961 | 992 | 1002 | 1061 | 1000 | 1039 | 973 | 1014 | 978 | 984 |
| 801 - 810 | 924 | 975 | 1010 | 963 | 970 | 974 | 994 | 1061 | 987 | 994 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 811 - 820 | 975 | 999 | 1054 | 1000 | 977 | 982 | 1017 | 1008 | 964 | 983 |
| 821 - 830 | 986 | 993 | 981 | 975 | 986 | 1023 | 1052 | 1008 | 965 | 1081 |
| 831 - 840 | 1039 | 957 | 963 | 1032 | 1007 | 997 | 1006 | 1014 | 955 | 1000 |
| 841 - 850 | 996 | 988 | 980 | 1049 | 1018 | 976 | 1021 | 988 | 1018 | 993 |
| 851 - 860 | 990 | 1027 | 967 | 976 | 997 | 981 | 947 | 1008 | 984 | 908 |
| 861 - 870 | 1011 | 1044 | 1037 | 1006 | 998 | 994 | 997 | 990 | 1042 | 989 |
| 871 - 880 | 942 | 1041 | 936 | 1050 | 1026 | 1043 | 994 | 1030 | 990 | 1000 |
| 881 - 890 | 1036 | 1007 | 969 | 1074 | 1025 | 994 | 1023 | 1054 | 984 | 1043 |
| 891 - 900 | 1100 | 1001 | 1022 | 999 | 984 | 991 | 967 | 1014 | 991 | 1046 |
| 901 - 910 | 1006 | 928 | 1072 | 1068 | 952 | 996 | 1005 | 967 | 1039 | 963 |
| 911 - 920 | 1044 | 935 | 988 | 996 | 975 | 971 | 995 | 944 | 978 | 1031 |
| 921 - 930 | 968 | 987 | 1018 | 1047 | 987 | 942 | 1029 | 1003 | 993 | 966 |
| 931 - 940 | 1047 | 1027 | 995 | 1026 | 962 | 1018 | 1009 | 989 | 1017 | 1024 |
| 941 - 950 | 992 | 954 | 995 | 1033 | 1022 | 1000 | 982 | 939 | 1003 | 1003 |
| 951 - 960 | 1022 | 979 | 990 | 962 | 1008 | 1060 | 1034 | 922 | 1004 | 980 |
| 961 - 970 | 993 | 984 | 953 | 961 | 977 | 986 | 989 | 1036 | 964 | 1005 |
| 971 - 980 | 1023 | 1043 | 1003 | 1018 | 1015 | 967 | 989 | 1014 | 985 | 994 |
| 981 - 990 | 1008 | 921 | 970 | 1010 | 1010 | 957 | 1085 | 985 | 982 | 980 |
| 991 - 1000 | 1007 | 994 | 1012 | 1024 | 997 | 1030 | 994 | 1005 | 955 | 974 |
| 1001 - 1010 | 942 | 1027 | 988 | 937 | 991 | 1043 | 959 | 965 | 957 | 994 |
| 1011 - 1020 | 991 | 958 | 989 | 993 | 962 | 990 | 1023 | 992 | 1049 | 912 |
| 1021 - 1030 | 956 | 957 | 1005 | 1012 | 998 | 1021 | 982 | 982 | 1008 | 905 |
| 1031 - 1040 | 992 | 958 | 1025 | 985 | 1014 | 967 | 991 | 978 | 989 | 983 |
| 1041 - 1050 | 989 | 998 | 967 | 1023 | 1010 | 1009 | 972 | 1002 | 1046 | 940 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 1051 - 1060 | 1003 | 907 | 1019 | 991 | 993 | 1000 | 1018 | 1005 | 986 | 995 |
| 1061 - 1070 | 991 | 1045 | 939 | 993 | 1013 | 967 | 1038 | 939 | 1010 | 1046 |
| 1071 - 1080 | 1032 | 1001 | 998 | 1019 | 965 | 964 | 1014 | 999 | 906 | 1016 |
| 1081 - 1090 | 1023 | 992 | 1049 | 1003 | 1015 | 1026 | 987 | 961 | 992 | 1013 |
| 1091 - 1100 | 1037 | 1018 | 971 | 989 | 934 | 1032 | 977 | 965 | 1016 | 1006 |
| 1101 - 1110 | 1042 | 979 | 1051 | 1004 | 927 | 938 | 1078 | 1017 | 1012 | 1031 |
| 1111 - 1120 | 1049 | 1068 | 1000 | 997 | 1041 | 1012 | 996 | 1031 | 1030 | 985 |
| 1121 - 1130 | 989 | 1011 | 1049 | 963 | 1027 | 1047 | 1038 | 1040 | 1004 | 993 |
| 1131 - 1140 | 994 | 1086 | 1031 | 1004 | 1109 | 1156 | 1087 | 1061 | 1045 | 1072 |
| 1141 - 1150 | 991 | 1010 | 1050 | 1007 | 1084 | 1070 | 1045 | 1060 | 1282 | 1147 |
| 1151 - 1160 | 1195 | 1186 | 1123 | 1187 | 1197 | 1240 | 1227 | 1245 | 1201 | 1099 |
| 1161 - 1170 | 1117 | 1119 | 1139 | 1150 | 1048 | 1138 | 1202 | 1154 | 1141 | 1136 |
| 1171 - 1180 | 1141 | 1149 | 1119 | 1172 | 1102 | 1134 | 1138 | 1201 | 1256 | 1380 |
| 1181 - 1190 | 1349 | 1203 | 1352 | 1318 | 1182 | 1200 | 1258 | 1318 | 1276 | 1335 |
| 1191 - 1200 | 1374 | 1447 | 1423 | 1446 | 1387 | 1354 | 1451 | 1423 | 1442 | 1470 |
| 1201 - 1210 | 1404 | 1314 | 1366 | 1376 | 1477 | 1371 | 1342 | 1431 | 1446 | 1479 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 1211 - 1220 | 1463 | 1406 | 1337 | 1360 | 1424 | 1459 | 1392 | 1425 | 1393 | 1578 |
| 1221 - 1230 | 1569 | 1533 | 1675 | 1519 | 1732 | 1671 | 1712 | 1667 | 1597 | 1539 |
| 1231 - 1240 | 1587 | 1583 | 1545 | 1533 | 1512 | 1451 | 1594 | 1515 | 1616 | 1560 |
| 1241 - 1250 | 1553 | 1522 | 1603 | 1661 | 1744 | 1674 | 1684 | 1627 | 1676 | 1784 |
| 1251 - 1260 | 1753 | 1701 | 1744 | 1692 | 1778 | 1663 | 1635 | 1736 | 1764 | 1738 |
| 1261 - 1270 | 1709 | 1643 | 1599 | 1651 | 1720 | 1685 | 1733 | 1692 | 1694 | 1704 |
| 1271 - 1280 | 1621 | 1686 | 1705 | 1657 | 1674 | 1722 | 1722 | 1677 | 1662 | 1676 |
| 1281 - 1290 | 1768 | 1667 | 1669 | 1736 | 1753 | 1704 | 1756 | 1763 | 1776 | 1690 |
| 1291 - 1300 | 1684 | 1759 | 1740 | 1811 | 1671 | 1743 | 1724 | 1729 | 1843 | 1756 |
| 1301 - 1310 | 1750 | 1770 | 1729 | 1717 | 1703 | 1728 | 1755 | 1711 | 1694 | 1720 |
| 1311 - 1320 | 1641 | 1638 | 1727 | 1651 | 1652 | 1645 | 1717 | 1795 | 1820 | 1729 |
| 1321 - 1330 | 1839 | 1827 | 1829 | 1772 | 1757 | 1729 | 1792 | 1749 | 1734 | 1746 |
| 1331 - 1340 | 1710 | 1793 | 1820 | 1795 | 1715 | 1793 | 1699 | 1752 | 1828 | 1785 |
| 1341 - 1350 | 1835 | 1723 | 1696 | 1656 | 1709 | 1782 | 1802 | 1780 | 1714 | 1798 |

Appendix D. Representative Sample of AIM Particle Count Data (Ambient Airport Sample Session 2)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 - 10 | 1394 | 1387 | 1382 | 1410 | 1433 | 1389 | 1427 | 1382 | 1400 | 1398 |
| 11 - 20 | 1389 | 1375 | 1330 | 1315 | 1339 | 1355 | 1385 | 1374 | 1398 | 1411 |
| 21 - 30 | 1404 | 1356 | 1392 | 1368 | 1348 | 1411 | 1456 | 1418 | 1372 | 1429 |
| 31 - 40 | 1399 | 1434 | 1353 | 1399 | 1393 | 1361 | 1414 | 1391 | 1388 | 1409 |
| 41 - 50 | 1410 | 1347 | 1354 | 1394 | 1424 | 1384 | 1439 | 1415 | 1383 | 1404 |
| 51 - 60 | 1481 | 1429 | 1345 | 1366 | 1401 | 1391 | 1419 | 1443 | 1403 | 1434 |
| 61 - 70 | 1324 | 1424 | 1411 | 1336 | 1383 | 1389 | 1426 | 1448 | 1366 | 1302 |
| 71 - 80 | 1258 | 1350 | 1363 | 1402 | 1336 | 1344 | 1409 | 1355 | 1394 | 1386 |
| 81 - 90 | 1380 | 1405 | 1498 | 1449 | 1435 | 1320 | 1366 | 1396 | 1365 | 1327 |
| 91 - 100 | 1347 | 1369 | 1384 | 1357 | 1461 | 1405 | 1365 | 1415 | 1403 | 1362 |
| 101 - 110 | 1450 | 1389 | 1455 | 1430 | 1458 | 1369 | 1365 | 1358 | 1418 | 1388 |
| 111 - 120 | 1410 | 1406 | 1356 | 1454 | 1426 | 1386 | 1448 | 1421 | 1347 | 1385 |
| 121 - 130 | 1427 | 1444 | 1465 | 1420 | 1482 | 1437 | 1459 | 1410 | 1474 | 1421 |
| 131 - 140 | 1436 | 1431 | 1452 | 1445 | 1458 | 1436 | 1385 | 1389 | 1398 | 1380 |
| 141 - 150 | 1416 | 1423 | 1361 | 1447 | 1531 | 1384 | 1405 | 1491 | 1452 | 1448 |
| 151 - 160 | 1399 | 1368 | 1349 | 1380 | 1336 | 1401 | 1420 | 1406 | 1356 | 1395 |
| 161 - 170 | 1322 | 1368 | 1392 | 1432 | 1437 | 1248 | 1469 | 1391 | 1370 | 1432 |
| 171 - 180 | 1391 | 1408 | 1369 | 1414 | 1383 | 1453 | 1331 | 1446 | 1359 | 1376 |
| 181 - 190 | 1317 | 1400 | 1426 | 1475 | 1409 | 1458 | 1309 | 1329 | 1405 | 1409 |
| 191 - 200 | 1463 | 1293 | 1399 | 1428 | 1453 | 1420 | 1464 | 1444 | 1432 | 1327 |
| 201 - 210 | 1361 | 1355 | 1356 | 1425 | 1373 | 1456 | 1364 | 1511 | 1414 | 1432 |
| 211 - 220 | 1389 | 1406 | 1348 | 1391 | 1453 | 1415 | 1308 | 1402 | 1436 | 1398 |
| 221 - 230 | 1407 | 1398 | 1381 | 1425 | 1403 | 1316 | 1359 | 1422 | 1363 | 1416 |
| 231 - 240 | 1416 | 1388 | 1457 | 1444 | 1409 | 1419 | 1408 | 1413 | 1468 | 1418 |
| 241 - 250 | 1424 | 1395 | 1387 | 1449 | 1391 | 1390 | 1403 | 1360 | 1357 | 1365 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 251 - 260 | 1434 | 1396 | 1353 | 1355 | 1377 | 1431 | 1392 | 1394 | 1437 | 1358 |
| 261 - 270 | 1387 | 1406 | 1456 | 1416 | 1393 | 1419 | 1443 | 1360 | 1495 | 1397 |
| 271 - 280 | 1427 | 1447 | 1396 | 1451 | 1437 | 1366 | 1413 | 1410 | 1377 | 1394 |
| 281 - 290 | 1380 | 1360 | 1447 | 1426 | 1447 | 1375 | 1302 | 1421 | 1372 | 1492 |
| 291 - 300 | 1421 | 1427 | 1398 | 1395 | 1372 | 1393 | 1403 | 1418 | 1405 | 1326 |
| 301 - 310 | 1478 | 1402 | 1341 | 1328 | 1455 | 1366 | 1365 | 1346 | 1429 | 1431 |
| 311 - 320 | 1426 | 1382 | 1448 | 1366 | 1440 | 1423 | 1437 | 1357 | 1310 | 1454 |
| 321 - 330 | 1397 | 1473 | 1393 | 1404 | 1413 | 1367 | 1419 | 1377 | 1417 | 1374 |
| 331 - 340 | 1375 | 1397 | 1464 | 1414 | 1508 | 1408 | 1459 | 1414 | 1333 | 1341 |
| 341 - 350 | 1476 | 1326 | 1436 | 1454 | 1389 | 1413 | 1399 | 1372 | 1429 | 1366 |
| 351 - 360 | 1362 | 1376 | 1345 | 1421 | 1384 | 1388 | 1397 | 1353 | 1410 | 1444 |
| 361 - 370 | 1407 | 1446 | 1412 | 1339 | 1426 | 1396 | 1386 | 1418 | 1447 | 1343 |
| 371 - 380 | 1318 | 1439 | 1380 | 1321 | 1392 | 1434 | 1390 | 1370 | 1427 | 1416 |
| 381 - 390 | 1384 | 1446 | 1410 | 1432 | 1385 | 1425 | 1496 | 1401 | 1402 | 1334 |
| 391 - 400 | 1378 | 1344 | 1389 | 1390 | 1368 | 1368 | 1423 | 1364 | 1456 | 1348 |
| 401 - 410 | 1380 | 1427 | 1445 | 1483 | 1412 | 1385 | 1362 | 1426 | 1353 | 1402 |
| 411 - 420 | 1372 | 1475 | 1417 | 1338 | 1440 | 1436 | 1467 | 1465 | 1428 | 1512 |
| 421 - 430 | 1396 | 1434 | 1404 | 1471 | 1413 | 1432 | 1449 | 1352 | 1472 | 1412 |
| 431 - 440 | 1421 | 1499 | 1451 | 1444 | 1343 | 1398 | 1406 | 1374 | 1395 | 1386 |
| 441 - 450 | 1402 | 1431 | 1477 | 1425 | 1447 | 1390 | 1448 | 1419 | 1389 | 1316 |
| 451 - 460 | 1363 | 1375 | 1432 | 1467 | 1463 | 1486 | 1432 | 1388 | 1408 | 1391 |
| 461 - 470 | 1430 | 1350 | 1443 | 1467 | 1433 | 1417 | 1457 | 1393 | 1382 | 1410 |
| 471 - 480 | 1410 | 1430 | 1471 | 1376 | 1453 | 1425 | 1508 | 1436 | 1430 | 1426 |
| 481 - 490 | 1381 | 1339 | 1465 | 1464 | 1486 | 1387 | 1403 | 1437 | 1393 | 1361 |
| 491 - 500 | 1456 | 1447 | 1428 | 1428 | 1409 | 1432 | 1474 | 1393 | 1455 | 1432 |
| 501 - 510 | 1362 | 1401 | 1389 | 1453 | 1351 | 1373 | 1448 | 1385 | 1429 | 1452 |
| 511 - 520 | 1408 | 1366 | 1490 | 1445 | 1490 | 1416 | 1447 | 1403 | 1371 | 1445 |
| 521 - 530 | 1463 | 1398 | 1392 | 1437 | 1383 | 1411 | 1494 | 1461 | 1431 | 1512 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 531 - 540 | 1461 | 1459 | 1415 | 1417 | 1451 | 1407 | 1405 | 1436 | 1430 | 1394 |
| 541 - 550 | 1405 | 1421 | 1437 | 1453 | 1369 | 1445 | 1420 | 1420 | 1354 | 1393 |
| 551 - 560 | 1428 | 1403 | 1389 | 1409 | 1406 | 1397 | 1438 | 1457 | 1356 | 1379 |
| 561 - 570 | 1423 | 1428 | 1454 | 1446 | 1460 | 1450 | 1410 | 1430 | 1430 | 1413 |
| 571 - 580 | 1448 | 1400 | 1446 | 1385 | 1452 | 1467 | 1461 | 1440 | 1494 | 1424 |
| 581 - 590 | 1386 | 1327 | 1419 | 1484 | 1397 | 1386 | 1419 | 1414 | 1472 | 1408 |
| 591 - 600 | 1415 | 1422 | 1479 | 1493 | 1413 | 1398 | 1378 | 1487 | 1408 | 1459 |
| 601 - 610 | 1440 | 1411 | 1441 | 1369 | 1434 | 1395 | 1382 | 1422 | 1433 | 1420 |
| 611 - 620 | 1465 | 1438 | 1476 | 1367 | 1454 | 1433 | 1441 | 1386 | 1490 | 1478 |
| 621 - 630 | 1493 | 1417 | 1437 | 1430 | 1390 | 1446 | 1385 | 1403 | 1452 | 1427 |
| 631 - 640 | 1457 | 1363 | 1371 | 1454 | 1454 | 1409 | 1386 | 1449 | 1406 | 1453 |
| 641 - 650 | 1432 | 1457 | 1476 | 1388 | 1447 | 1393 | 1466 | 1456 | 1384 | 1442 |
| 651 - 660 | 1423 | 1460 | 1477 | 1386 | 1414 | 1432 | 1416 | 1416 | 1446 | 1461 |
| 661 - 670 | 1469 | 1413 | 1398 | 1361 | 1413 | 1429 | 1389 | 1414 | 1389 | 1354 |
| 671 - 680 | 1479 | 1424 | 1420 | 1443 | 1496 | 1437 | 1482 | 1400 | 1398 | 1444 |
| 681 - 690 | 1392 | 1422 | 1468 | 1481 | 1493 | 1411 | 1401 | 1478 | 1428 | 1461 |
| 691 - 700 | 1412 | 1469 | 1504 | 1507 | 1384 | 1404 | 1351 | 1402 | 1376 | 1427 |
| 701 - 710 | 1414 | 1473 | 1404 | 1371 | 1419 | 1446 | 1461 | 1360 | 1430 | 1475 |
| 711 - 720 | 1457 | 1471 | 1397 | 1434 | 1411 | 1414 | 1420 | 1444 | 1525 | 1482 |
| 721 - 730 | 1513 | 1415 | 1463 | 1432 | 1436 | 1392 | 1405 | 1521 | 1506 | 1527 |
| 731 - 740 | 1444 | 1452 | 1433 | 1437 | 1447 | 1490 | 1508 | 1463 | 1423 | 1490 |
| 741 - 750 | 1471 | 1509 | 1530 | 1499 | 1447 | 1525 | 1475 | 1500 | 1468 | 1435 |
| 751 - 760 | 1507 | 1483 | 1512 | 1477 | 1517 | 1526 | 1445 | 1470 | 1432 | 1360 |
| 761 - 770 | 1487 | 1445 | 1495 | 1477 | 1498 | 1441 | 1456 | 1445 | 1461 | 1476 |
| 771 - 780 | 1483 | 1487 | 1510 | 1493 | 1568 | 1476 | 1467 | 1529 | 1492 | 1431 |
| 781 - 790 | 1488 | 1505 | 1529 | 1535 | 1459 | 1499 | 1484 | 1425 | 1461 | 1496 |
| 791 - 800 | 1518 | 1445 | 1441 | 1445 | 1501 | 1509 | 1448 | 1509 | 1464 | 1536 |
| 801 - 810 | 1526 | 1460 | 1485 | 1476 | 1602 | 1437 | 1422 | 1452 | 1439 | 1480 |

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|---|---|---|---|---|---|---|---|---|---|---|
| 811 - 820 | 1466 | 1495 | 1435 | 1497 | 1466 | 1488 | 1538 | 1482 | 1483 | 1461 |
| 821 - 830 | 1445 | 1601 | 1453 | 1500 | 1536 | 1443 | 1472 | 1542 | 1466 | 1378 |
| 831 - 840 | 1492 | 1469 | 1456 | 1435 | 1419 | 1498 | 1503 | 1459 | 1477 | 1418 |
| 841 - 850 | 1455 | 1425 | 1461 | 1491 | 1435 | 1461 | 1405 | 1449 | 1454 | 1459 |
| 851 - 860 | 1502 | 1496 | 1496 | 1439 | 1441 | 1447 | 1419 | 1494 | 1418 | 1441 |
| 861 - 870 | 1449 | 1522 | 1453 | 1385 | 1417 | 1438 | 1449 | 1502 | 1510 | 1427 |
| 871 - 880 | 1452 | 1504 | 1430 | 1488 | 1452 | 1492 | 1479 | 1463 | 1485 | 1447 |
| 881 - 890 | 1432 | 1414 | 1455 | 1458 | 1491 | 1486 | 1470 | 1529 | 1535 | 1519 |
| 891 - 900 | 1566 | 1480 | 1518 | 1514 | 1435 | 1530 | 1444 | 1453 | 1587 | 1521 |
| 901 - 910 | 1615 | 1558 | 1514 | 1651 | 1541 | 1585 | 1523 | 1512 | 1612 | 1651 |
| 911 - 920 | 1586 | 1566 | 1582 | 1654 | 1542 | 1619 | 1588 | 1612 | 1488 | 1509 |
| 921 - 930 | 1573 | 1511 | 1510 | 1539 | 1587 | 1601 | 1463 | 1574 | 1556 | 1502 |
| 931 - 940 | 1576 | 1524 | 1547 | 1544 | 1630 | 1589 | 1563 | 1552 | 1487 | 1583 |
| 941 - 950 | 1580 | 1638 | 1543 | 1609 | 1554 | 1640 | 1570 | 1578 | 1514 | 1502 |
| 951 - 960 | 1505 | 1573 | 1546 | 1653 | 1571 | 1562 | 1497 | 1636 | 1597 | 1630 |
| 961 - 970 | 1496 | 1618 | 1567 | 1653 | 1629 | 1566 | 1600 | 1613 | 1593 | 1507 |
| 971 - 980 | 1666 | 1609 | 1558 | 1591 | 1606 | 1553 | 1555 | 1563 | 1506 | 1636 |
| 981 - 990 | 1528 | 1598 | 1615 | 1535 | 1571 | 1530 | 1539 | 1553 | 1642 | 1552 |
| 991 - 1000 | 1557 | 1501 | 1530 | 1521 | 1473 | 1521 | 1552 | 1558 | 1581 | 1515 |
| 1001 - 1010 | 1498 | 1568 | 1569 | 1613 | 1594 | 1592 | 1582 | 1566 | 1635 | 1613 |
| 1011 - 1020 | 1545 | 1548 | 1542 | 1571 | 1614 | 1620 | 1566 | 1628 | 1596 | 1595 |
| 1021 - 1030 | 1527 | 1558 | 1583 | 1556 | 1573 | 1533 | 1558 | 1541 | 1476 | 1512 |
| 1031 - 1040 | 1512 | 1480 | 1540 | 1554 | 1548 | 1511 | 1505 | 1458 | 1620 | 1572 |
| 1041 - 1050 | 1478 | 1468 | 1648 | 1509 | 1516 | 1474 | 1499 | 1512 | 1451 | 1501 |

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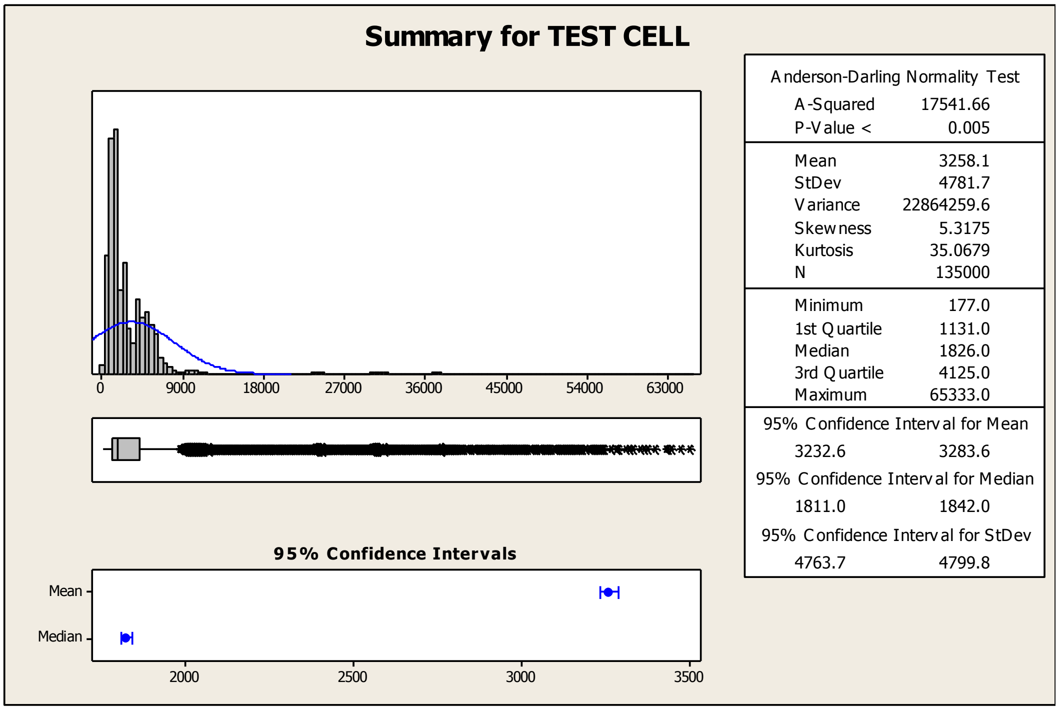
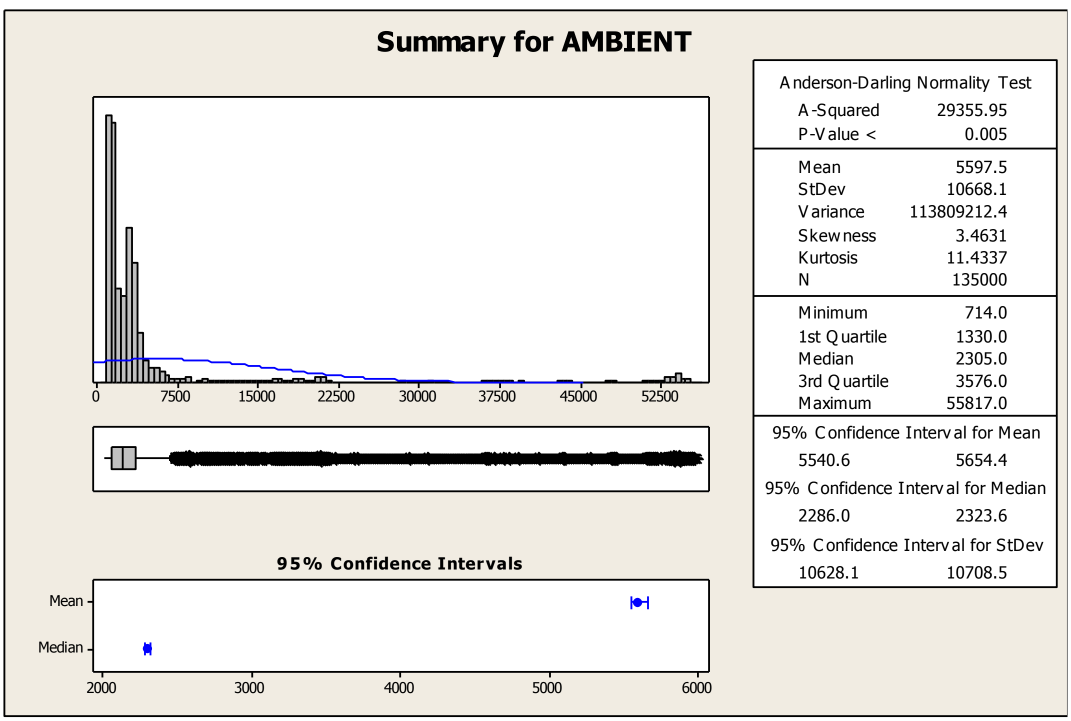
| 1051 - 1060 | 1569 | 1528 | 1552 | 1538 | 1571 | 1634 | 1492 | 1564 | 1615 | 1577 |
| 1061 - 1070 | 1639 | 1556 | 1574 | 1570 | 1580 | 1571 | 1658 | 1542 | 1567 | 1517 |
| 1071 - 1080 | 1555 | 1555 | 1604 | 1501 | 1584 | 1535 | 1558 | 1544 | 1535 | 1524 |
| 1081 - 1090 | 1520 | 1586 | 1613 | 1523 | 1556 | 1530 | 1544 | 1581 | 1576 | 1489 |
| 1091 - 1100 | 1543 | 1490 | 1575 | 1526 | 1602 | 1621 | 1581 | 1597 | 1531 | 1551 |
| 1101 - 1110 | 1519 | 1531 | 1596 | 1565 | 1545 | 1506 | 1564 | 1531 | 1471 | 1503 |
| 1111 - 1120 | 1520 | 1487 | 1551 | 1557 | 1640 | 1567 | 1551 | 1560 | 1530 | 1582 |
| 1121 - 1130 | 1577 | 1545 | 1560 | 1512 | 1654 | 1563 | 1609 | 1509 | 1517 | 1517 |
| 1131 - 1140 | 1559 | 1507 | 1588 | 1585 | 1521 | 1564 | 1549 | 1594 | 1564 | 1524 |
| 1141 - 1150 | 1550 | 1594 | 1489 | 1495 | 1481 | 1548 | 1575 | 1519 | 1522 | 1552 |
| 1151 - 1160 | 1482 | 1502 | 1535 | 1555 | 1509 | 1497 | 1550 | 1512 | 1540 | 1467 |
| 1161 - 1170 | 1461 | 1493 | 1500 | 1473 | 1546 | 1620 | 1533 | 1624 | 1577 | 1484 |
| 1171 - 1180 | 1465 | 1536 | 1529 | 1545 | 1526 | 1503 | 1529 | 1510 | 1565 | 1486 |
| 1181 - 1190 | 1566 | 1577 | 1545 | 1459 | 1541 | 1491 | 1606 | 1546 | 1533 | 1414 |
| 1191 - 1200 | 1412 | 1564 | 1461 | 1488 | 1550 | 1452 | 1497 | 1517 | 1518 | 1549 |
| 1201 - 1210 | 1492 | 1518 | 1537 | 1548 | 1530 | 1471 | 1475 | 1447 | 1453 | 1573 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1211 - 1220 | 1471 | 1543 | 1547 | 1521 | 1473 | 1479 | 1498 | 1534 | 1552 | 1482 |
| 1221 - 1230 | 1540 | 1564 | 1510 | 1530 | 1536 | 1524 | 1505 | 1551 | 1530 | 1489 |
| 1231 - 1240 | 1502 | 1492 | 1488 | 1399 | 1521 | 1505 | 1538 | 1529 | 1490 | 1499 |
| 1241 - 1250 | 1498 | 1565 | 1497 | 1503 | 1467 | 1450 | 1479 | 1520 | 1527 | 1572 |
| 1251 - 1260 | 1455 | 1497 | 1482 | 1431 | 1445 | 1474 | 1449 | 1441 | 1512 | 1424 |
| 1261 - 1270 | 1497 | 1504 | 1486 | 1464 | 1433 | 1493 | 1535 | 1531 | 1495 | 1418 |
| 1271 - 1280 | 1528 | 1499 | 1378 | 1442 | 1486 | 1460 | 1454 | 1421 | 1417 | 1479 |
| 1281 - 1290 | 1476 | 1521 | 1494 | 1537 | 1464 | 1591 | 1473 | 1508 | 1414 | 1451 |
| 1291 - 1300 | 1519 | 1483 | 1433 | 1490 | 1469 | 1430 | 1466 | 1532 | 1420 | 1418 |
| 1301 - 1310 | 1449 | 1377 | 1417 | 1512 | 1449 | 1461 | 1464 | 1501 | 1457 | 1481 |
| 1311 - 1320 | 1475 | 1452 | 1422 | 1493 | 1419 | 1421 | 1397 | 1463 | 1454 | 1463 |
| 1321 - 1330 | 1531 | 1385 | 1417 | 1542 | 1449 | 1450 | 1463 | 1440 | 1450 | 1501 |
| 1331 - 1340 | 1501 | 1458 | 1506 | 1522 | 1392 | 1498 | 1494 | 1478 | 1394 | 1532 |
| 1341 - 1350 | 1488 | 1472 | 1524 | 1553 | 1403 | 1504 | 1467 | 1454 | 1432 | 1492 |

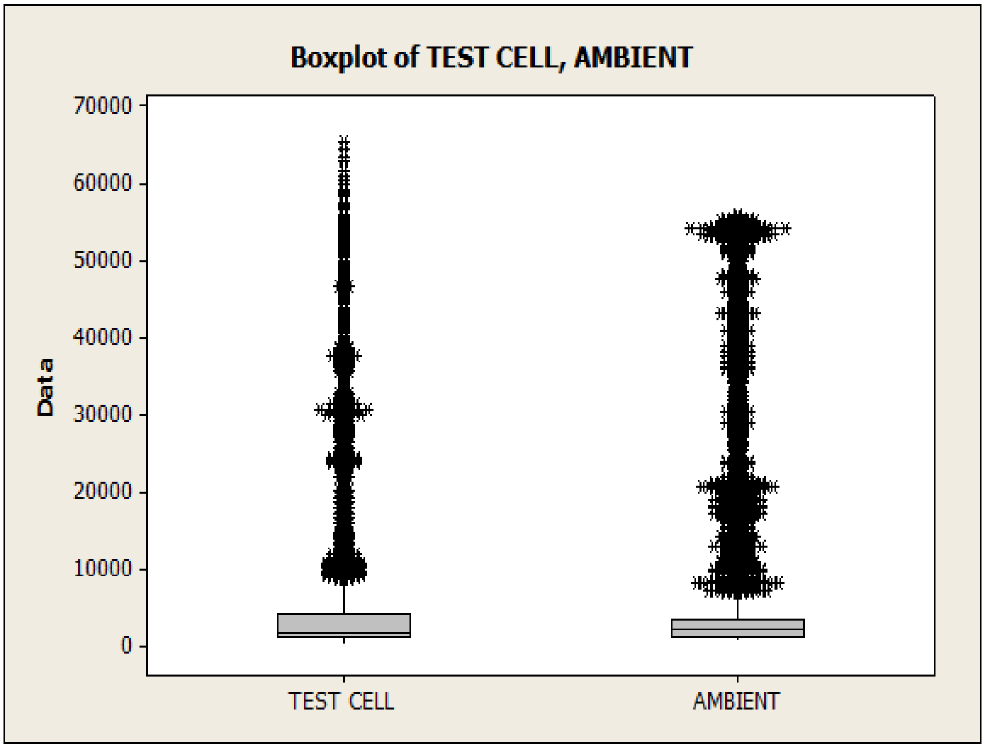
Appendix E. Minitab Data



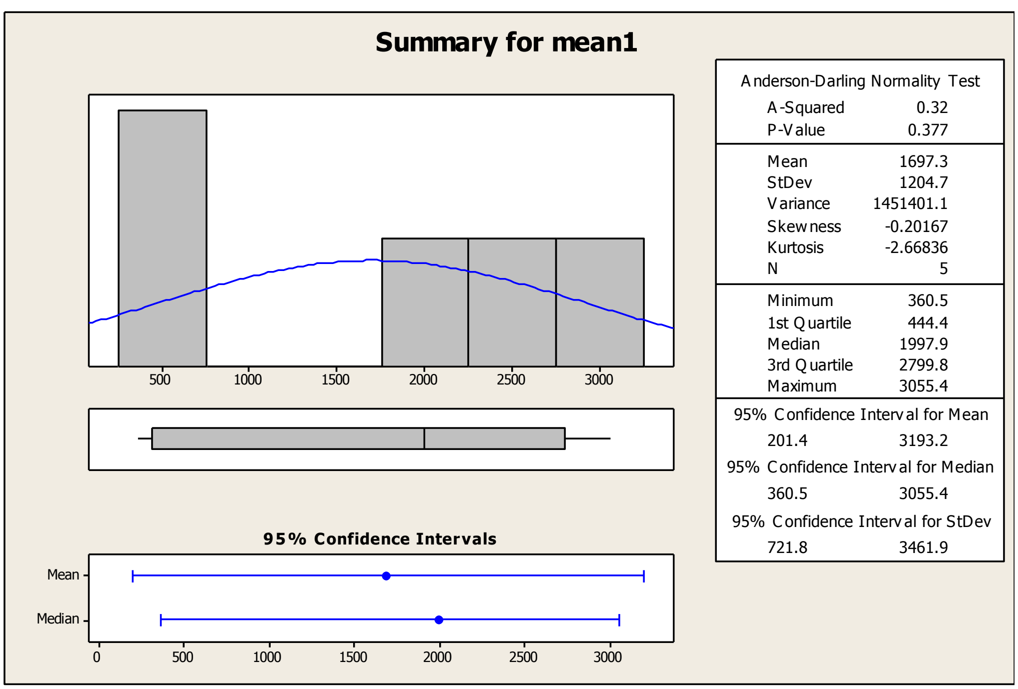

Test Cell Population Statistical Summary



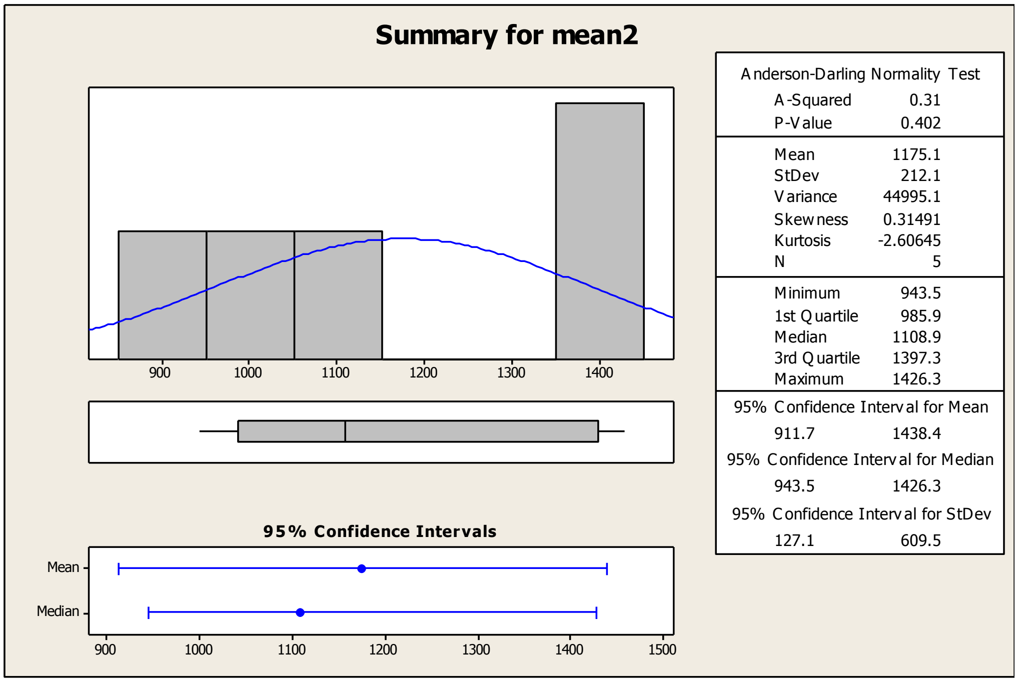

Ambient Airport Statistical Summary



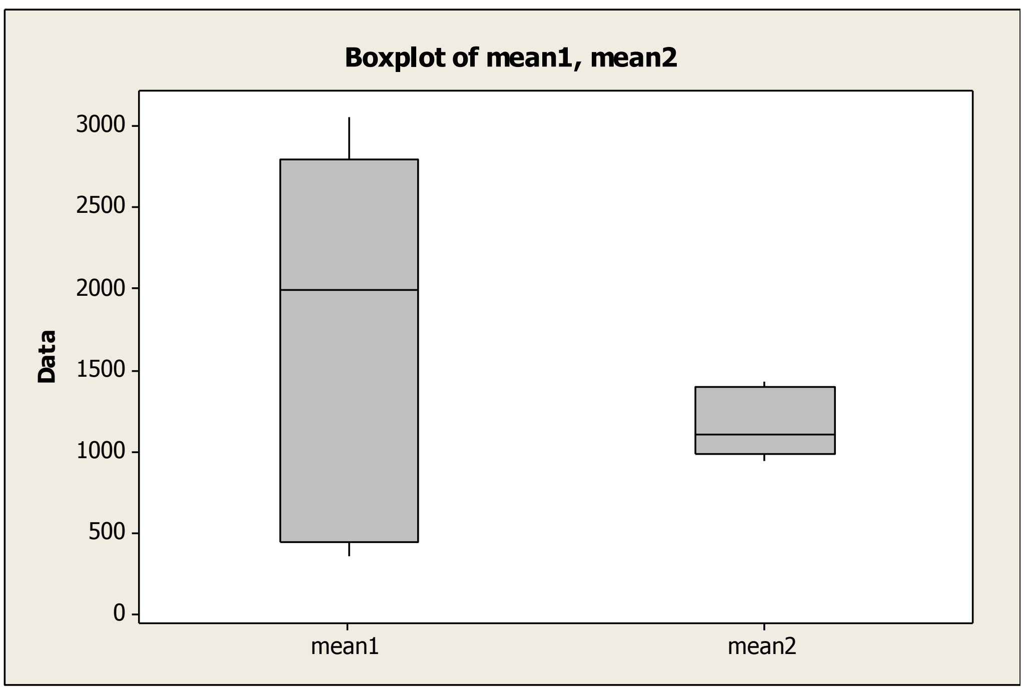

Population Comparison



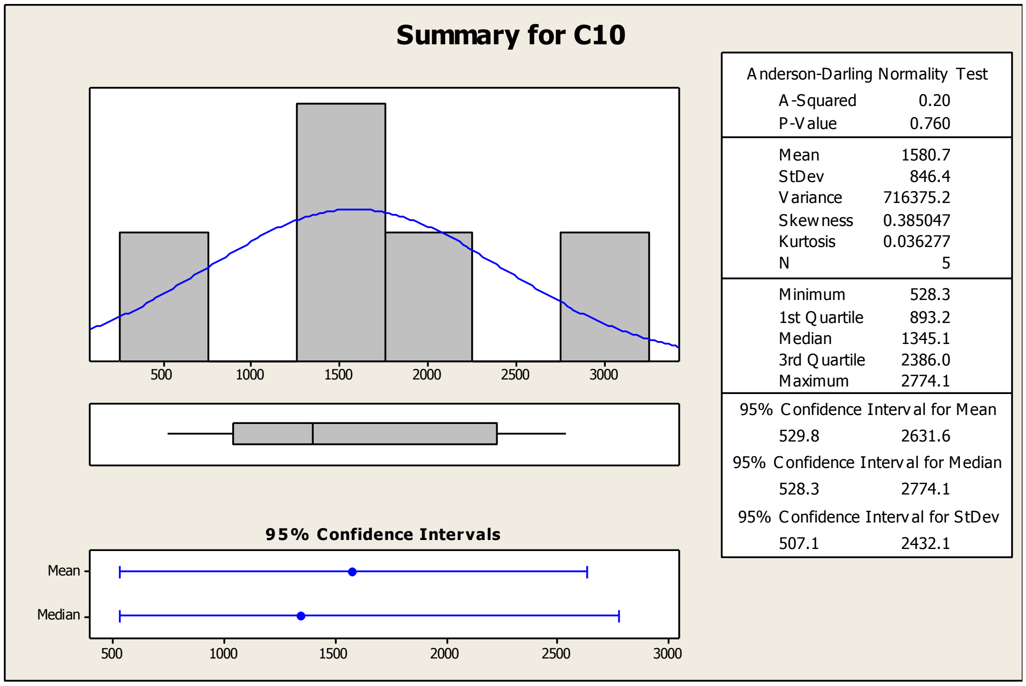

Summary, test cell random sample 1



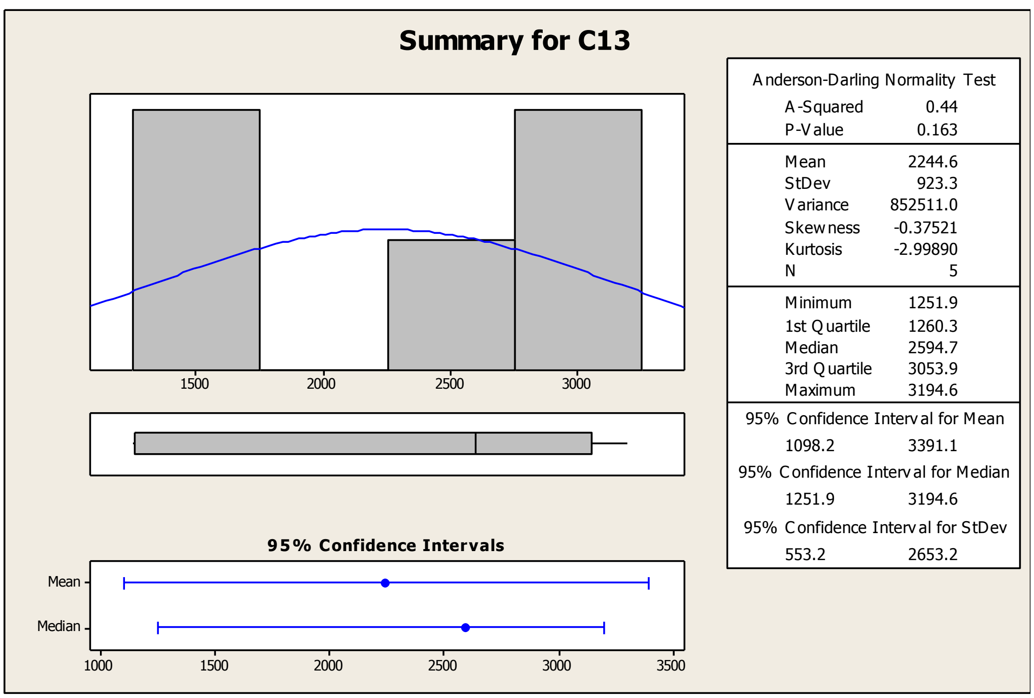

Summary, airport random sample 1



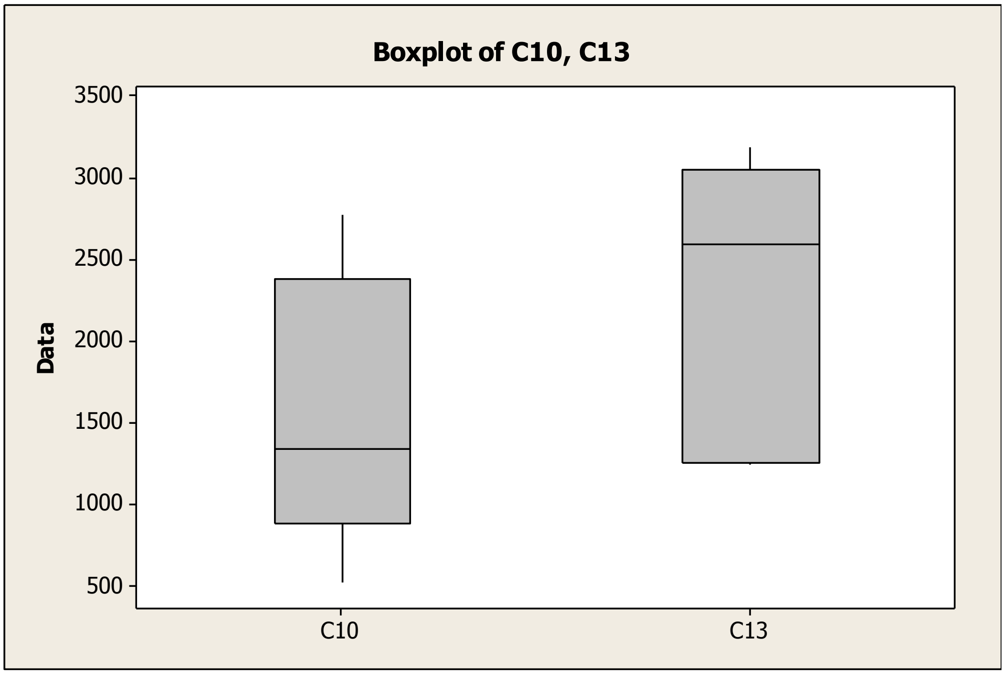

Back to back boxplot random sample 1



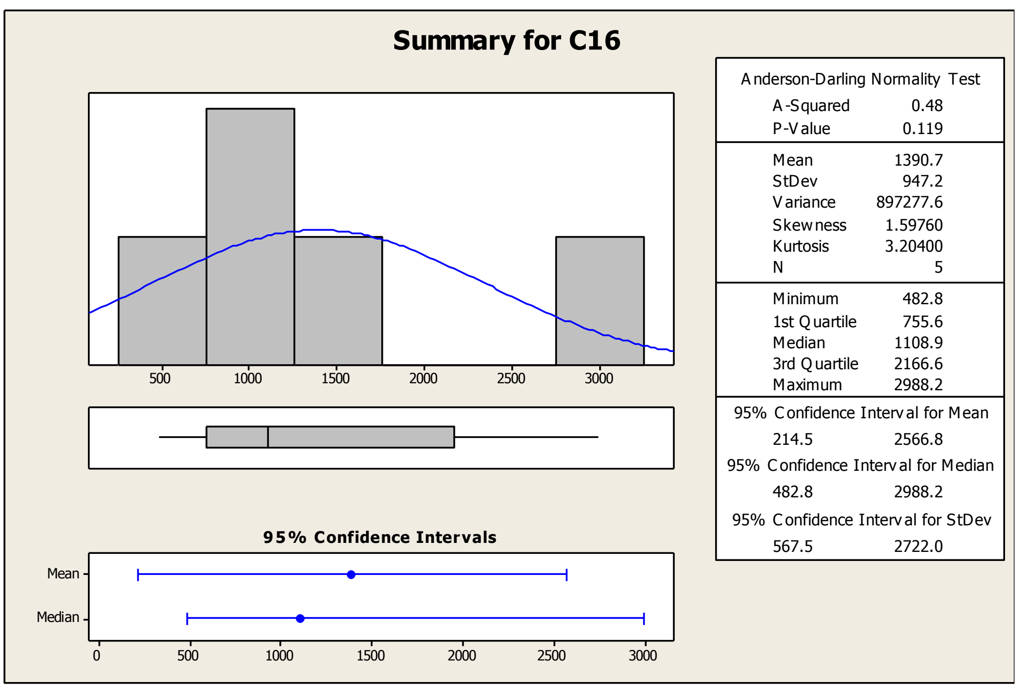

Summary, test cell random sample 2



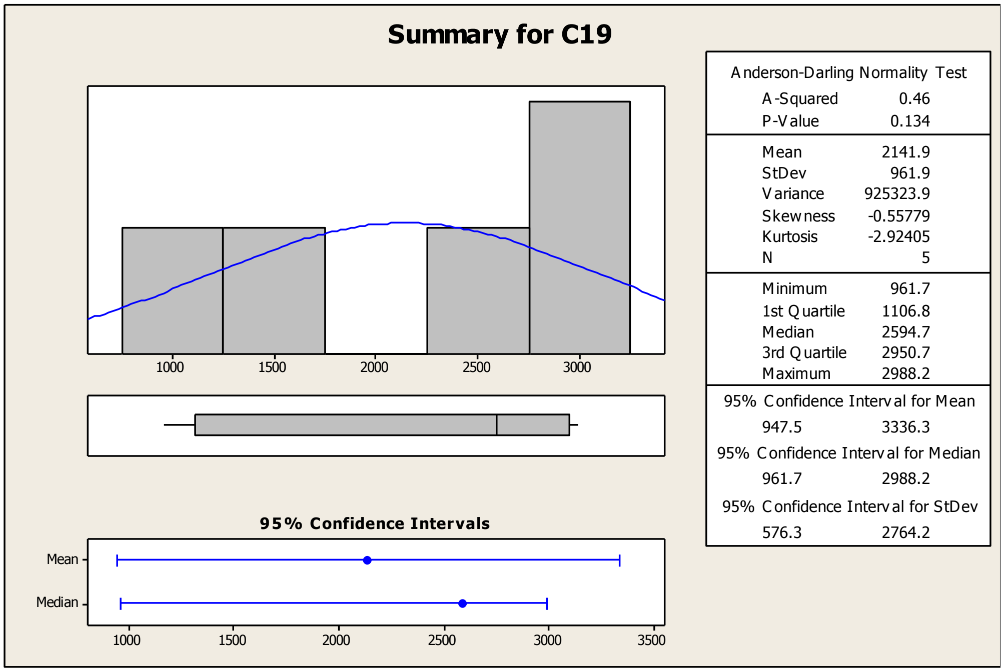

Summary, airport random sample 2



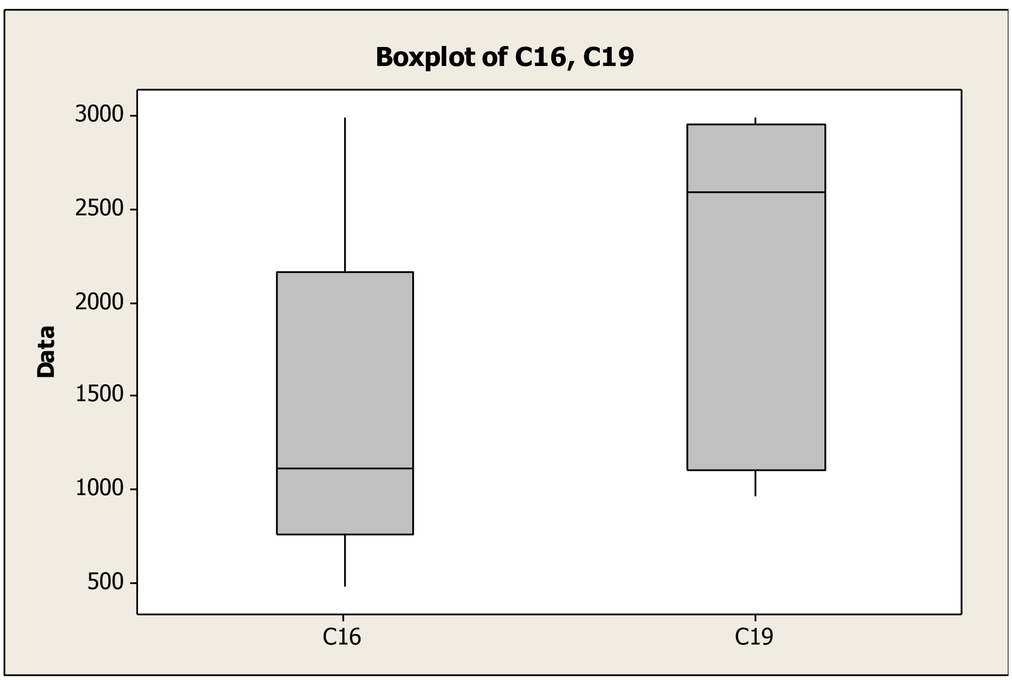

Back to back boxplot random sample 2




Summary, test cell random sample 3




Summary, airport random sample 3




Back to back boxplot of random sample 3

Appendix F. Stable Sample Segment Averages

| TEST CELL | time | particle count | | Ambient | time | particle count | |
|---|---|---|---|---|---|---|---|
| 2.31 | 44 | 2705 | 2774.133 | 1.1 | 45 | 947 | 961.6667 |
| 1 | 45 | 2709 | | | 46 | 995 | |
| | 46 | 2772 | | | 47 | 934 | |
| | 47 | 2712 | | | 48 | 972 | |
| | 48 | 2659 | | | 49 | 947 | |
| | 49 | 2837 | | | 50 | 986 | |
| | 50 | 2855 | | | 51 | 967 | |
| | 51 | 2955 | | | 52 | 986 | |
| | 52 | 2813 | | | 53 | 992 | |
| | 53 | 2789 | | | 54 | 905 | |
| | 54 | 2715 | | | 55 | 991 | |
| | 55 | 2726 | | | 56 | 994 | |
| | 56 | 2680 | | | 57 | 901 | |
| | 57 | 2877 | | | 58 | 953 | |
| | 58 | 2808 | | | 59 | 955 | |
| | | | | | | | |
| 2.32 | 80 | 2839 | 2818 | 1.3 | 12 | 1035 | 1060.938 |
| 2 | 81 | 2783 | | | 13 | 1017 | |
| | 82 | 2684 | | | 14 | 1059 | |
| | 83 | 2695 | | | 15 | 1100 | |
| | 84 | 2781 | | | 16 | 1053 | |
| | 85 | 2704 | | | 17 | 996 | |
| | 86 | 2743 | | | 18 | 1115 | |
| | 87 | 2728 | | | 19 | 1107 | |
| | 88 | 2843 | | | 20 | 1095 | |
| | 89 | 2917 | | | 21 | 1035 | |
| | 90 | 2905 | | | 22 | 1075 | |
| | 91 | 2891 | | | 23 | 1037 | |
| | 92 | 2881 | | | 24 | 1056 | |
| | 93 | 2876 | | | 25 | 1075 | |
| | 94 | 2855 | | | 26 | 1048 | |
| | 95 | 2963 | | | 27 | 1072 | |
| | | | | | | | |
| 2.6 | 10 | 1415 | 1393.313 | 1.8 | 70 | 1083 | 1028.333 |
| 3 | 11 | 1439 | | | 71 | 1006 | |
| | 12 | 1416 | | | 72 | 981 | |
| | 13 | 1351 | | | 73 | 1038 | |
| | 14 | 1358 | | | 74 | 986 | |
| | 15 | 1426 | | | 75 | 1042 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 16 | 1386 | | | 76 | 1006 | |
| | 17 | 1391 | | | 77 | 1037 | |
| | 18 | 1381 | | | 78 | 1054 | |
| | 19 | 1432 | | | 79 | 1044 | |
| | 20 | 1367 | | | 80 | 991 | |
| | 21 | 1444 | | | 81 | 1027 | |
| | 22 | 1373 | | | 82 | 1026 | |
| | 23 | 1367 | | | 83 | 1052 | |
| | 24 | 1374 | | | 84 | 1052 | |
| | | | | | | | |
| 2.12 | 50 | 1341 | 1285 | 1.11 | 35 | 975 | 1048 |
| 4 | 51 | 1383 | | | 36 | 1089 | |
| | 52 | 1256 | | | 37 | 1093 | |
| | 53 | 1299 | | | 38 | 1044 | |
| | 54 | 1207 | | | 39 | 1008 | |
| | 55 | 1298 | | | 40 | 1077 | |
| | 56 | 1317 | | | 41 | 1065 | |
| | 57 | 1284 | | | 42 | 1064 | |
| | 58 | 1308 | | | 43 | 1058 | |
| | 59 | 1259 | | | 44 | 1048 | |
| | 60 | 1220 | | | 45 | 1014 | |
| | 61 | 1292 | | | 46 | 1066 | |
| | 62 | 1288 | | | 47 | 1048 | |
| | 63 | 1229 | | | 48 | 1013 | |
| | 64 | 1276 | | | 49 | 1064 | |
| | 65 | 1303 | | | 50 | 1042 | |
| | | | | | | | |
| 2.22 | 32 | 2529 | 2544.267 | 1.18 | 6 | 900 | 943.5333 |
| 5 | 33 | 2624 | | | 7 | 1030 | |
| | 34 | 2439 | | | 8 | 936 | |
| | 35 | 2555 | | | 9 | 941 | |
| | 36 | 2618 | | | 10 | 954 | |
| | 37 | 2515 | | | 11 | 996 | |
| | 38 | 2618 | | | 12 | 899 | |
| | 39 | 2549 | | | 13 | 941 | |
| | 40 | 2462 | | | 14 | 981 | |
| | 41 | 2557 | | | 15 | 949 | |
| | 42 | 2557 | | | 16 | 936 | |
| | 43 | 2580 | | | 17 | 950 | |
| | 44 | 2584 | | | 18 | 917 | |
| | 45 | 2513 | | | 19 | 945 | |
| | 46 | 2464 | | | 20 | 878 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3.2 | 50 | 1018 | 980.8125 | 2.1 | 96 | 1340 | 1268.688 |
| 6 | 51 | 999 | | | 97 | 1212 | |
| | 52 | 974 | | | 98 | 1328 | |
| | 53 | 986 | | | 99 | 1274 | |
| | 54 | 1026 | | | 100 | 1305 | |
| | 55 | 955 | | | 101 | 1275 | |
| | 56 | 992 | | | 102 | 1238 | |
| | 57 | 1005 | | | 103 | 1264 | |
| | 58 | 968 | | | 104 | 1259 | |
| | 59 | 945 | | | 105 | 1227 | |
| | 60 | 1000 | | | 106 | 1277 | |
| | 61 | 941 | | | 107 | 1236 | |
| | 62 | 941 | | | 108 | 1290 | |
| | 63 | 935 | | | 109 | 1174 | |
| | 64 | 996 | | | 110 | 1352 | |
| | 65 | 1012 | | | 111 | 1248 | |
| 3.6 | 76 | 2006 | 1997.933 | 2.6 | 35 | 1169 | 1108.867 |
| 7 | 77 | 2077 | | | 36 | 1148 | |
| | 78 | 2044 | | | 37 | 1105 | |
| | 79 | 1946 | | | 38 | 1114 | |
| | 80 | 1957 | | | 39 | 1132 | |
| | 81 | 1998 | | | 40 | 1094 | |
| | 82 | 1987 | | | 41 | 1136 | |
| | 83 | 1953 | | | 42 | 1074 | |
| | 84 | 1986 | | | 43 | 1090 | |
| | 85 | 2025 | | | 44 | 1118 | |
| | 86 | 1979 | | | 45 | 1103 | |
| | 87 | 2062 | | | 46 | 1103 | |
| | 88 | 1953 | | | 47 | 1130 | |
| | 89 | 2058 | | | 48 | 992 | |
| | 90 | 1938 | | | 49 | 1125 | |
| 3.13 | 30 | 1036 | 1061.2 | 2.12 | 50 | 1368 | 1405.733 |
| 8 | 31 | 1094 | | | 51 | 1415 | |
| | 32 | 1037 | | | 52 | 1395 | |
| | 33 | 1081 | | | 53 | 1472 | |
| | 34 | 1039 | | | 54 | 1417 | |
| | 35 | 1019 | | | 55 | 1378 | |
| | 36 | 1038 | | | 56 | 1435 | |
| | 37 | 1089 | | | 57 | 1440 | |
| | 38 | 1052 | | | 58 | 1360 | |
| | 39 | 1034 | | | 59 | 1465 | |
| | 40 | 1045 | | | 60 | 1330 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 41 | 1056 | | | 61 | 1370 | |
| | 42 | 1085 | | | 62 | 1424 | |
| | 43 | 1100 | | | 63 | 1372 | |
| | 44 | 1113 | | | 64 | 1445 | |
| | | | | | | | |
| 3.15 | 40 | 1323 | 1235.533 | 2.14 | 100 | 1462 | 1426.333 |
| 9 | 41 | 1206 | | | 101 | 1374 | |
| | 42 | 1262 | | | 102 | 1341 | |
| | 43 | 1227 | | | 103 | 1462 | |
| | 44 | 1125 | | | 104 | 1414 | |
| | 45 | 1217 | | | 105 | 1475 | |
| | 46 | 1233 | | | 106 | 1444 | |
| | 47 | 1249 | | | 107 | 1393 | |
| | 48 | 1230 | | | 108 | 1435 | |
| | 49 | 1263 | | | 109 | 1467 | |
| | 50 | 1197 | | | 110 | 1410 | |
| | 51 | 1263 | | | 111 | 1412 | |
| | 52 | 1203 | | | 112 | 1411 | |
| | 53 | 1209 | | | 113 | 1438 | |
| | 54 | 1326 | | | 114 | 1457 | |
| | | | | | | | |
| 3.23 | 64 | 1320 | 1345.067 | 2.22 | 42 | 1275 | 1251.867 |
| 10 | 65 | 1363 | | | 43 | 1259 | |
| | 66 | 1333 | | | 44 | 1278 | |
| | 67 | 1366 | | | 45 | 1189 | |
| | 68 | 1359 | | | 46 | 1291 | |
| | 69 | 1358 | | | 47 | 1298 | |
| | 70 | 1327 | | | 48 | 1206 | |
| | 71 | 1275 | | | 49 | 1225 | |
| | 72 | 1377 | | | 50 | 1224 | |
| | 73 | 1322 | | | 51 | 1256 | |
| | 74 | 1344 | | | 52 | 1241 | |
| | 75 | 1389 | | | 53 | 1303 | |
| | 76 | 1366 | | | 54 | 1229 | |
| | 77 | 1342 | | | 55 | 1267 | |
| | 78 | 1335 | | | 56 | 1237 | |
| | | | | | | | |
| 4.14a | 30 | 4008 | 3974.533 | 3.18 | 96 | 1942 | 1860.6 |
| 11 | 31 | 3947 | | | 97 | 1923 | |
| | 32 | 3945 | | | 98 | 1885 | |
| | 33 | 3946 | | | 99 | 1869 | |
| | 34 | 4042 | | | 100 | 1848 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 35 | 4059 | | | 101 | 1851 | |
| | 36 | 3942 | | | 102 | 1853 | |
| | 37 | 4011 | | | 103 | 1913 | |
| | 38 | 4019 | | | 104 | 1804 | |
| | 39 | 3939 | | | 105 | 1797 | |
| | 40 | 3806 | | | 106 | 1862 | |
| | 41 | 3979 | | | 107 | 1891 | |
| | 42 | 3931 | | | 108 | 1897 | |
| | 43 | 4043 | | | 109 | 1808 | |
| | 44 | 4001 | | | 110 | 1766 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4.14a | 90 | 3840 | 3804 | 3.19 | 30 | 1845 | 1827.33 |
| 12 | 91 | 3763 | | | 31 | 1759 | |
| | 92 | 3909 | | | 32 | 1859 | |
| | 93 | 3769 | | | 33 | 1785 | |
| | 94 | 3699 | | | 34 | 1766 | |
| | 95 | 3866 | | | 35 | 1898 | |
| | 96 | 3839 | | | 36 | 1924 | |
| | 97 | 3805 | | | 37 | 1796 | |
| | 98 | 3741 | | | 38 | 1849 | |
| | 99 | 3795 | | | 39 | 1782 | |
| | 100 | 3790 | | | 40 | 1822 | |
| | 101 | 3921 | | | 41 | 1773 | |
| | 102 | 3745 | | | 42 | 1837 | |
| | 103 | 3773 | | | 43 | 1846 | |
| | 104 | 3805 | | | 44 | 1869 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4.12 | 40 | 3962 | 3876.333 | 3.22 | 80 | 2974 | 2913.2 |
| 13 | 41 | 3887 | | | 81 | 2952 | |
| | 42 | 3855 | | | 82 | 2859 | |
| | 43 | 3874 | | | 83 | 2897 | |
| | 44 | 3807 | | | 84 | 2921 | |
| | 45 | 3824 | | | 85 | 2872 | |
| | 46 | 3806 | | | 86 | 2931 | |
| | 47 | 4057 | | | 87 | 2874 | |
| | 48 | 3826 | | | 88 | 2922 | |
| | 49 | 3805 | | | 89 | 3069 | |
| | 50 | 3984 | | | 90 | 2932 | |
| | 51 | 3791 | | | 91 | 2877 | |
| | 52 | 3855 | | | 92 | 2834 | |
| | 53 | 3886 | | | 93 | 2835 | |
| | 54 | 3926 | | | 94 | 2949 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4.17 | 60 | 4082 | 4284.067 | 2.23 | 45 | 2990 | 2988.2 |
| 14 | 61 | 4050 | | | 46 | 2945 | |
| | 62 | 4124 | | | 47 | 3032 | |
| | 63 | 4184 | | | 48 | 2946 | |
| | 64 | 4207 | | | 49 | 3096 | |
| | 65 | 4206 | | | 50 | 3025 | |
| | 66 | 4147 | | | 51 | 2906 | |
| | 67 | 4210 | | | 52 | 3024 | |
| | 68 | 4329 | | | 53 | 2915 | |
| | 69 | 4285 | | | 54 | 2928 | |
| | 70 | 4559 | | | 55 | 3015 | |
| | 71 | 4437 | | | 56 | 3004 | |
| | 72 | 4567 | | | 57 | 3019 | |
| | 73 | 4523 | | | 58 | 3049 | |
| | 74 | 4351 | | | 59 | 2929 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4.21 | 40 | 2623 | 2572.73 | 3.29 | 80 | 3328 | 3194.6 |
| 15 | 41 | 2614 | | | 81 | 3201 | |
| | 42 | 2601 | | | 82 | 3119 | |
| | 43 | 2448 | | | 83 | 3296 | |
| | 44 | 2635 | | | 84 | 3321 | |
| | 45 | 2494 | | | 85 | 3196 | |
| | 46 | 2686 | | | 86 | 3307 | |
| | 47 | 2559 | | | 87 | 3169 | |
| | 48 | 2489 | | | 88 | 3264 | |
| | 49 | 2559 | | | 89 | 3142 | |
| | 50 | 2548 | | | 90 | 3087 | |
| | 51 | 2540 | | | 91 | 3133 | |
| | 52 | 2598 | | | 92 | 2993 | |
| | 53 | 2589 | | | 93 | 3167 | |
| | 54 | 2608 | | | 94 | 3196 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1.14 | 50 | 427 | 482.8 | 4.1 | 35 | 1436 | 1368.26 |
| 16 | 51 | 443 | | | 36 | 1418 | |
| | 52 | 451 | | | 37 | 1370 | |
| | 53 | 494 | | | 38 | 1380 | |
| | 54 | 529 | | | 39 | 1339 | |
| | 55 | 477 | | | 40 | 1363 | |
| | 56 | 497 | | | 41 | 1278 | |
| | 57 | 485 | | | 42 | 1324 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 58 | 502 | | | 43 | 1309 | |
| | 59 | 492 | | | 44 | 1378 | |
| | 60 | 524 | | | 45 | 1427 | |
| | 61 | 489 | | | 46 | 1418 | |
| | 62 | 484 | | | 47 | 1406 | |
| | 63 | 487 | | | 48 | 1339 | |
| | 64 | 461 | | | 49 | 1339 | |
| 1.15 | 10 | 355 | 360.533 | 4.2 | 60 | 1581 | 1475.8 |
| 17 | 11 | 380 | | | 61 | 1477 | |
| | 12 | 344 | | | 62 | 1493 | |
| | 13 | 365 | | | 63 | 1596 | |
| | 14 | 348 | | | 64 | 1536 | |
| | 15 | 363 | | | 65 | 1473 | |
| | 16 | 379 | | | 66 | 1587 | |
| | 17 | 324 | | | 67 | 1555 | |
| | 18 | 329 | | | 68 | 1532 | |
| | 19 | 383 | | | 69 | 1364 | |
| | 20 | 369 | | | 70 | 1410 | |
| | 21 | 361 | | | 71 | 1410 | |
| | 22 | 377 | | | 72 | 1396 | |
| | 23 | 364 | | | 73 | 1367 | |
| | 24 | 367 | | | 74 | 1360 | |
| 1.20 | 73 | 594 | 528.333 | 4.5 | 47 | 2160 | 2210.73 |
| 18 | 74 | 561 | | | 48 | 2119 | |
| | 75 | 502 | | | 49 | 2295 | |
| | 76 | 520 | | | 50 | 2256 | |
| | 77 | 503 | | | 51 | 2213 | |
| | 78 | 515 | | | 52 | 2291 | |
| | 79 | 551 | | | 53 | 2091 | |
| | 80 | 548 | | | 54 | 2240 | |
| | 81 | 476 | | | 55 | 2151 | |
| | 82 | 517 | | | 56 | 2341 | |
| | 83 | 524 | | | 57 | 2185 | |
| | 84 | 490 | | | 58 | 2241 | |
| | 85 | 572 | | | 59 | 2286 | |
| | 86 | 525 | | | 60 | 2143 | |
| | 87 | 527 | | | 61 | 2149 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | 3246.73 |
| 1.22 | 35 | 3153 | 3055.4 | 4.10 | 55 | 3104 | 3 |
| 19 | 36 | 3083 | | | 56 | 3124 | |
| | 37 | 3140 | | | 57 | 3505 | |
| | 38 | 3167 | | | 58 | 3203 | |
| | 39 | 3092 | | | 59 | 3318 | |
| | 40 | 3051 | | | 60 | 3401 | |
| | 41 | 2993 | | | 61 | 3054 | |
| | 42 | 2982 | | | 62 | 3263 | |
| | 43 | 3065 | | | 63 | 3432 | |
| | 44 | 3028 | | | 64 | 3248 | |
| | 45 | 3026 | | | 65 | 3015 | |
| | 46 | 2989 | | | 66 | 3138 | |
| | 47 | 2976 | | | 67 | 3258 | |
| | 48 | 3071 | | | 68 | 3448 | |
| | 49 | 3015 | | | 69 | 3190 | |
| 1.24 | 76 | 432 | 441.066 | 4.16 | 10 | 2589 | 2594.73 |
| 20 | 77 | 451 | | | 11 | 2603 | |
| | 78 | 483 | | | 12 | 2662 | |
| | 79 | 416 | | | 13 | 2720 | |
| | 80 | 472 | | | 14 | 2654 | |
| | 81 | 448 | | | 15 | 2613 | |
| | 82 | 382 | | | 16 | 2659 | |
| | 83 | 448 | | | 17 | 2650 | |
| | 84 | 452 | | | 18 | 2700 | |
| | 85 | 454 | | | 19 | 2654 | |
| | 86 | 444 | | | 20 | 2594 | |
| | 87 | 435 | | | 21 | 2468 | |
| | 88 | 436 | | | 22 | 2371 | |
| | 89 | 428 | | | 23 | 2498 | |
| | 90 | 435 | | | 24 | 2486 | |

Appendix G. Minitab Data Printout

POPULATION

### Descriptive Statistics: TEST CELL

```
Variable        N  N*    Mean  SE Mean   StDev  Minimum      Q1  Median      Q3
TEST CELL  135000   0  3258.1     13.0  4781.7    177.0  1131.0  1826.0  4125.0

Variable   Maximum
TEST CELL  65333.0
```

### Descriptive Statistics: AMBIENT

```
Variable       N  N*    Mean  SE Mean    StDev  Minimum      Q1  Median      Q3
AMBIENT   135000   0  5597.5     29.0  10668.1    714.0  1330.0  2305.0  3576.0

Variable  Maximum
AMBIENT   55817.0
```

### Two-Sample T-Test and CI: mean1, mean2

```
Two-sample T for mean1 vs mean2

       N  Mean  StDev  SE Mean
mean1  5  1697   1205      539
mean2  5  1175    212       95


Difference = mu (mean1) - mu (mean2)
Estimate for difference:  522
95% CI for difference:  (-997, 2041)
T-Test of difference = 0 (vs not =): T-Value = 0.95  P-Value = 0.394  DF = 4
```

### Two-Sample T-Test and CI: C10, C13

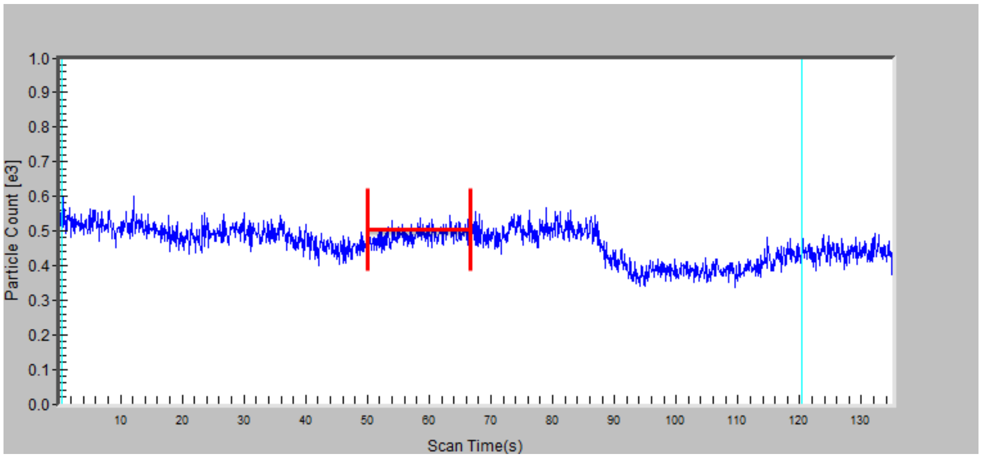
```
Two-sample T for C10 vs C13

     N  Mean  StDev  SE Mean
C10  5  1581    846      379
C13  5  2245    923      413


Difference = mu (C10) - mu (C13)
Estimate for difference:  -664
95% CI for difference:  (-1988, 661)
T-Test of difference = 0 (vs not =): T-Value = -1.19  P-Value = 0.275  DF = 7
```

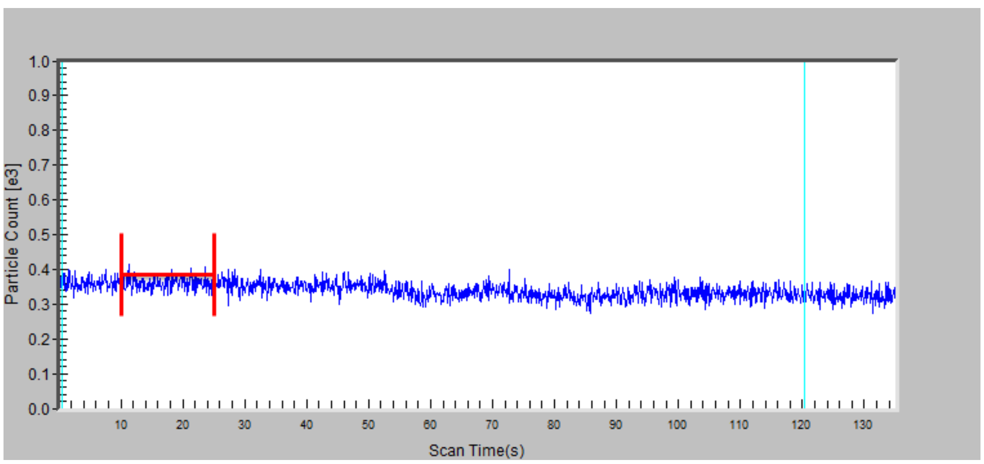
### Two-Sample T-Test and CI: C16, C19

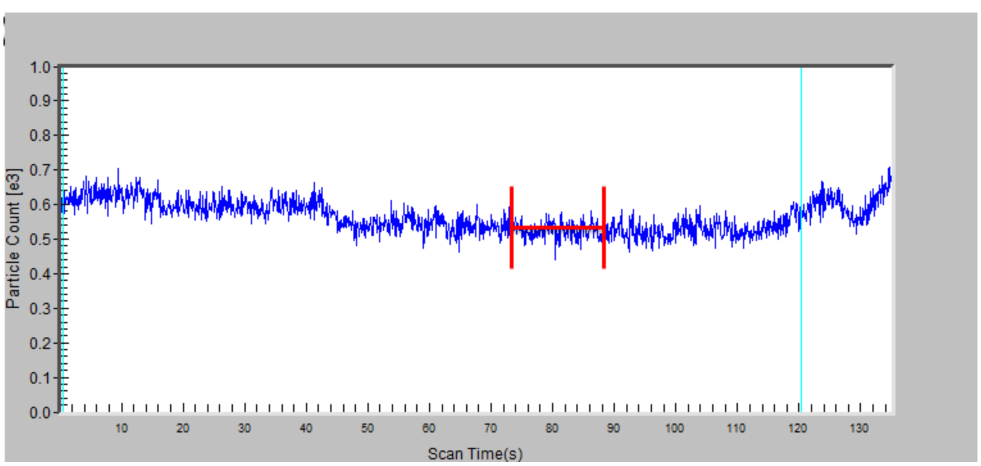
```
Two-sample T for C16 vs C19

     N  Mean  StDev  SE Mean
C16  5  1391    947      424
```

```
C19  5  2142    962      430


Difference = mu (C16) - mu (C19)
Estimate for difference:  -751
95% CI for difference:  (-2179, 676)
T-Test of difference = 0 (vs not =): T-Value = -1.24  P-Value =` DF = 7
```

Appendix H. Representative Sample of Stable Sample Segments



Appendix I. T-distribution Table

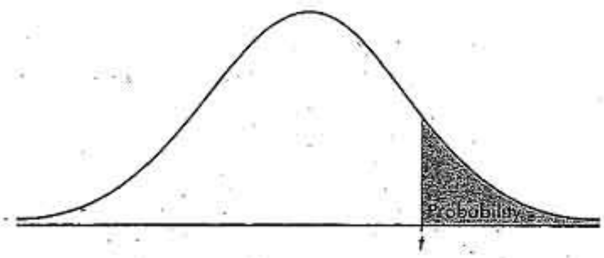



**TABLE B: $t$-DISTRIBUTION CRITICAL VALUES**

| | Tail probability $p$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| df | .25 | .20 | .15 | .10 | .05 | .025 | .02 | .01 | .005 | .0025 | .001 | .0005 |
| 1 | 1.000 | 1.376 | 1.963 | 3.078 | 6.314 | 12.71 | 15.89 | 31.82 | 63.66 | 127.3 | 318.3 | 636.6 |
| 2 | .816 | 1.061 | 1.386 | 1.886 | 2.920 | 4.303 | 4.849 | 6.965 | 9.925 | 14.09 | 22.33 | 31.60 |
| 3 | .765 | .978 | 1.250 | 1.638 | 2.353 | 3.182 | 3.482 | 4.541 | 5.841 | 7.453 | 10.21 | 12.92 |
| 4 | .741 | .941 | 1.190 | 1.533 | 2.132 | 2.776 | 2.999 | 3.747 | 4.604 | 5.598 | 7.173 | 8.610 |
| 5 | .727 | .920 | 1.156 | 1.476 | 2.015 | 2.571 | 2.757 | 3.365 | 4.032 | 4.773 | 5.893 | 6.869 |
| 6 | .718 | .906 | 1.134 | 1.440 | 1.943 | 2.447 | 2.612 | 3.143 | 3.707 | 4.317 | 5.208 | 5.959 |
| 7 | .711 | .896 | 1.119 | 1.415 | 1.895 | 2.365 | 2.517 | 2.998 | 3.499 | 4.029 | 4.785 | 5.408 |
| 8 | .706 | .889 | 1.108 | 1.397 | 1.860 | 2.306 | 2.449 | 2.896 | 3.355 | 3.833 | 4.501 | 5.041 |
| 9 | .703 | .883 | 1.100 | 1.383 | 1.833 | 2.262 | 2.398 | 2.821 | 3.250 | 3.690 | 4.297 | 4.781 |
| 10 | .700 | .879 | 1.093 | 1.372 | 1.812 | 2.228 | 2.359 | 2.764 | 3.169 | 3.581 | 4.144 | 4.587 |
| 11 | .697 | .876 | 1.088 | 1.363 | 1.796 | 2.201 | 2.328 | 2.718 | 3.106 | 3.497 | 4.025 | 4.437 |
| 12 | .695 | .873 | 1.083 | 1.356 | 1.782 | 2.179 | 2.303 | 2.681 | 3.055 | 3.428 | 3.930 | 4.318 |
| 13 | .694 | .870 | 1.079 | 1.350 | 1.771 | 2.160 | 2.282 | 2.650 | 3.012 | 3.372 | 3.852 | 4.221 |
| 14 | .692 | .868 | 1.076 | 1.345 | 1.761 | 2.145 | 2.264 | 2.624 | 2.977 | 3.326 | 3.787 | 4.140 |
| 15 | .691 | .866 | 1.074 | 1.341 | 1.753 | 2.131 | 2.249 | 2.602 | 2.947 | 3.286 | 3.733 | 4.073 |
| 16 | .690 | .865 | 1.071 | 1.337 | 1.746 | 2.120 | 2.235 | 2.583 | 2.921 | 3.252 | 3.686 | 4.015 |
| 17 | .689 | .863 | 1.069 | 1.333 | 1.740 | 2.110 | 2.224 | 2.567 | 2.898 | 3.222 | 3.646 | 3.965 |
| 18 | .688 | .862 | 1.067 | 1.330 | 1.734 | 2.101 | 2.214 | 2.552 | 2.878 | 3.197 | 3.611 | 3.922 |
| 19 | .688 | .861 | 1.066 | 1.328 | 1.729 | 2.093 | 2.205 | 2.539 | 2.861 | 3.174 | 3.579 | 3.883 |
| 20 | .687 | .860 | 1.064 | 1.325 | 1.725 | 2.086 | 2.197 | 2.528 | 2.845 | 3.153 | 3.552 | 3.850 |
| 21 | .686 | .859 | 1.063 | 1.323 | 1.721 | 2.080 | 2.189 | 2.518 | 2.831 | 3.135 | 3.527 | 3.819 |
| 22 | .686 | .858 | 1.061 | 1.321 | 1.717 | 2.074 | 2.183 | 2.508 | 2.819 | 3.119 | 3.505 | 3.792 |
| 23 | .685 | .858 | 1.060 | 1.319 | 1.714 | 2.069 | 2.177 | 2.500 | 2.807 | 3.104 | 3.485 | 3.768 |
| 24 | .685 | .857 | 1.059 | 1.318 | 1.711 | 2.064 | 2.172 | 2.492 | 2.797 | 3.091 | 3.467 | 3.745 |
| 25 | .684 | .856 | 1.058 | 1.316 | 1.708 | 2.060 | 2.167 | 2.485 | 2.787 | 3.078 | 3.450 | 3.725 |
| 26 | .684 | .856 | 1.058 | 1.315 | 1.706 | 2.056 | 2.162 | 2.479 | 2.779 | 3.067 | 3.435 | 3.707 |
| 27 | .684 | .855 | 1.057 | 1.314 | 1.703 | 2.052 | 2.158 | 2.473 | 2.771 | 3.057 | 3.421 | 3.690 |
| 28 | .683 | .855 | 1.056 | 1.313 | 1.701 | 2.048 | 2.154 | 2.467 | 2.763 | 3.047 | 3.408 | 3.674 |
| 29 | .683 | .854 | 1.055 | 1.311 | 1.699 | 2.045 | 2.150 | 2.462 | 2.756 | 3.038 | 3.396 | 3.659 |
| 30 | .683 | .854 | 1.055 | 1.310 | 1.697 | 2.042 | 2.147 | 2.457 | 2.750 | 3.030 | 3.385 | 3.646 |
| 40 | .681 | .851 | 1.050 | 1.303 | 1.684 | 2.021 | 2.123 | 2.423 | 2.704 | 2.971 | 3.307 | 3.551 |
| 50 | .679 | .849 | 1.047 | 1.299 | 1.676 | 2.009 | 2.109 | 2.403 | 2.678 | 2.937 | 3.261 | 3.496 |
| 60 | .679 | .848 | 1.045 | 1.296 | 1.671 | 2.000 | 2.099 | 2.390 | 2.660 | 2.915 | 3.232 | 3.460 |
| 80 | .678 | .846 | 1.043 | 1.292 | 1.664 | 1.990 | 2.088 | 2.374 | 2.639 | 2.887 | 3.195 | 3.416 |
| 100 | .677 | .845 | 1.042 | 1.290 | 1.660 | 1.984 | 2.081 | 2.364 | 2.626 | 2.871 | 3.174 | 3.390 |
| 1000 | .675 | .842 | 1.037 | 1.282 | 1.646 | 1.962 | 2.056 | 2.330 | 2.581 | 2.813 | 3.098 | 3.300 |
| ∞ | .674 | .841 | 1.036 | 1.282 | 1.645 | 1.960 | 2.054 | 2.326 | 2.576 | 2.807 | 3.091 | 3.291 |
| | 50% | 60% | 70% | 80% | 90% | 95% | 96% | 98% | 99% | 99.5% | 99.8% | 99.9% |
| | Confidence level $C$ | | | | | | | | | | | |

# Appendix J. Model 3776 CPC Schematic